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PHILOSOPHICAL TRANSACTIONS.

I. *On the Tides of the Arctic Seas.*

By the Rev. SAMUEL HAUGHTON, *M.D. Dubl., D.C.L. Oxon, F.R.S.,*
Fellow of Trinity College, Dublin.

Part VII. *Tides of Port Kennedy, in Bellot Strait.* (*Final Discussion.*)

Received February 17,—Read March 15, 1877.

[PLATE 1.]

IN Part VI. I have discussed MCCLINTOCK'S observations on the Tides of Port Kennedy, using only the Heights and Times of High and Low Water, as I wished to follow the same method in comparing all the Tidal observations in the Arctic Seas. Although I adopted this method for the purpose of comparison, I was well aware that I had not exhausted all the information at my disposal, for MCCLINTOCK'S observations were made hourly during 23 days, and I used of these observations only those in the neighbourhood of H.W. and L.W. of Diurnal and Semidiurnal Tides. I shall now discuss the observations, with the aid of FOURIER'S Theorem, so that all the observations made at every hour of each day shall enter into the constants determined for that day. If F denote the height of the tide, observed at every hour of the day, we have by FOURIER'S Theorem

$$F = A_0 + A_1 \cos s + A_2 \cos 2s + A_3 \cos 3s + \&c.$$
$$B_1 \sin s + B_2 \sin 2s + B_3 \sin 3s + \&c. \quad \ldots\ldots\ldots (1)$$

where s denotes the sun's hour angle, and where the coefficients A_0, A_1, B_1, A_2, B_2, &c., are found from the following equations, in which F_0, F_1, F_2, &c., denote the values of F at the hours 0, 1, 2, &c., 23.

$$24A_0 = F_0 + F_1 \ldots + F_{23} \quad \ldots\ldots\ldots\ldots (2)$$

$$\begin{aligned}12A_1=&(F_0-F_{12}).\\&+\{(F_1+F_{23})-(7_{11}+F_{13})\}\cos\phi\\&+\{(F_2+F_{22})-(F_{10}+F_{14})\}\cos 2\phi\\&+\{(F_3+F_{21})-(F_9+F_{15})\}\cos 3\phi\\&+\{(F_4+F_{20})-(F_8+F_{16})\}\cos 4\phi\\&+\{(F_5+F_{19})-(F_7+F_{17})\}\cos 5\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)\end{aligned}$$

$$\begin{aligned}12B_1=&(F_6-F_{18}).\\&+\{(F_1+F_{11})-(F_{13}+F_{23})\}\sin\phi\\&+\{(F_2+F_{10})-(F_{14}+F_{22})\}\sin 2\phi\\&+\{(F_3+F_9)-(F_{15}+F_{21})\}\sin 3\phi\\&+\{(F_4+F_8)-(F_{16}+F_{20})\}\sin 4\phi\\&+\{(F_5+F_7)-(F_{17}+F_{19})\}\sin 5\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)\end{aligned}$$

$$\begin{aligned}12A_2=&(F_0+F_{12})-(F_6+F_{18}).\\&+\left\{\begin{matrix}(F_1+F_{23})+(F_{11}+F_{13})\\-(F_5+F_{19})-(F_7+F_{17})\end{matrix}\right\}\cos 2\phi\\&+\left\{\begin{matrix}(F_2+F_{22})+(F_{10}+F_{14})\\-(F_4+F_{20})-(F_8+F_{16})\end{matrix}\right\}\cos 4\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)\end{aligned}$$

$$\begin{aligned}12B_2=&(F_3+F_{15})-(F_9+F_{21}).\\&+\left\{\begin{matrix}(F_1+F_5)+(F_{13}+F_{17})\\-(F_7+F_{11})-(F_{19}+F_{23})\end{matrix}\right\}\sin 2\phi\\&+\left\{\begin{matrix}(F_2+F_4)+(F_{14}+F_{16})\\-(F_8+F_{10})-(F_{20}+F_{22})\end{matrix}\right\}\sin 4\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)\end{aligned}$$

$$\begin{aligned}12A_3=&(F_0+F_6+F_{12})-(F_6+F_{18}+F_{24}).\\&\left\{\begin{matrix}(F_1+F_{23})+(F_7+F_{17})+(F_{13}+F_{19})\\-(F_5+F_{21})-(F_9+F_{15})-(F_{11}+F_{23})\end{matrix}\right\}\cos 3\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)\end{aligned}$$

$$\begin{aligned}12B_3=&(F_3+F_{12}+F_{15})-(F_9+F_{14}+F_{22}).\\&\left\{\begin{matrix}(F_1+F_{11})+(F_5+F_9)+(F_{17}+F_{19})\\-(F_5+F_7)-(F_{13}+F_{23})-(F_{15}+F_{21})\end{matrix}\right\}\sin 3\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)\end{aligned}$$

In these equations $\phi=\frac{360}{24}=15°$.

Applying the foregoing equations to the hourly observations at Port Kennedy already published in Part VI., we find the following values of the Coefficients, which contain implicitly the 24 observations made on each day :—

TABLE I.—Tidal Coefficients for July, 1859, at Port Kennedy.

		A_0	A_1	B_1	A_2	B_2	A_3	B_3
1859.—July	6	75·6	− 3·8	−12·7	−19·9	+11·2	+0·1	+1·7
,,	7	79·6	− 5·9	−12·6	−18·3	− 0·9	−2·2	−1·3
,,	8	82·1	− 9·0	− 6·8	−14·2	− 8·7	−1·3	−1·6
,,	9	92·2	−12·8	− 4·6	− 8·8	−16·1	+0·0	+0·6
,,	10	95·8	−15·4	− 4·9	− 0·8	−11·4	+1·8	−1·6
,,	11	98·1	−14·1	− 6·5	+ 5·4	− 3·7	−3·6	+3·2
,,	12	88·3	−17·4	−12·4	+15·6	− 6·2	+0·4	+0·6
,,	13	92·9	−23·9	−15·8	+18·7	− 1·3	−0·4	−1·1
,,	14	92·9	−21·7	−20·3	+20·8	+ 5·2	+0·9	−0·5
,,	15	89·7	−11·5	−17·3	+18·1	+ 5·9	+0·5	+2·4
,,	16	93·5	−13·5	−22·5	+14·2	+15·6	+1·4	+1·1
,,	17	93·4	− 9·9	−21·1	+ 8·5	+20·5	+1·3	+1·4
,,	18	91·2	− 5·2	−15·3	+ 4·5	+19·9	−0·3	+2·1
,,	19	89·5	− 4·1	−15·1	− 2·7	+20·4	−0·9	+1·4
,,	20	89·8	− 4·7	−14·3	− 8·4	+18·7	−0·5	+1·6
,,	21	85·5	− 3·8	− 8·5	−11·7	+12·6	+0·0	+2·4
,,	22	83·5	− 5·5	− 7·2	−11·1	+ 7·9	+2·7	+2·0
,,	23	82·0	− 8·8	− 4·5	−13·9	− 3·0	+0·2	+0·2
,,	24	85·0	−12·2	− 3·6	−10·6	− 6·3	+0·8	−1·6
,,	25	88·0	−18·6	− 4·1	− 3·0	−11·1	−0·3	−1·1
,,	26	94·2	−20·0	− 8·6	− 1·9	−14·3	−0·3	+1·6
,,	27	102·6	−26·9	−21·2	+13·0	−10·9	−1·4	−5·2

The seven Coefficients of the preceding Table are drawn to scale in Plate* I., and they ought to show a fortnightly Tide.

I. *The Fortnightly Change of Mean Level.*

This Tide is represented by the Column A_0.

If we write

$$A_0 = a_0 + a_1 \cos u + a_2 \cos 2u + \&c. + b_1 \sin u + b_2 \sin 2u + \&c.$$

where u is an angle passing through all its changes in 14 days, we have

$$14a_0 = F_0 + F_1 + \&c. \ldots + F_{13} \quad (9)$$

$$7a_1 = (F_0 - F_7) + \{(F_1 + F_{13}) - (F_6 + F_8)\} \cos\phi + \{(F_2 + F_{12}) - (F_5 + F_9)\} \cos 2\phi + \{(F_3 + F_{11}) - (F_4 + F_{10})\} \cos 3\phi \quad (10)$$

$$7b_1 = \{(F_1 + F_6) - (F_8 + F_{13})\} \sin\phi + \{(F_2 + F_5) - (F_9 + F_{12})\} \sin 2\phi + \{(F_3 + F_4) - (F_{10} + F_{11})\} \sin 3\phi \quad (11)$$

where $\phi = \frac{360^\circ}{14}$.

* In this Plate, the vertical coordinates are inches, and the horizontal coordinates are days of the month.

From these equations we readily obtain—

TABLE II.—A_ϕ.

a_0. inches.	a_1. inches.	b_1. inches.
88·9	−5·4	−0·8
90·6	−3·4	−0·8
91·0	−2·7	−0·4
91·2	−2·5	−0·3
90·4	−2·9	−1·7
89·7	−2·5	−3·2
88·9	−1·6	−4·3
89·4	+2·4	−4·0
90·1	+3·8	−4·0
Mean 90·02	−1·64	−2·17

These numbers differ so much, that we must conclude it to be impossible, from the limited number of observations made, to deduce the law of the Fortnightly Change in the Mean Level of the water.

II. *The Diurnal Tide.*

The Diurnal Tide is represented by the expression

$$A_1 \cos s + B_1 \sin s,$$

in which the coefficients A_1 and B_1 are to be expanded by means of a fortnightly arc, as in the case of the coefficient A_ϕ.

Let

$$A_1 = a_0 + a_1 \cos u + a_2 \cos 2u + \&c. + b_1 \sin u + b_2 \sin 2u + \&c. \quad (12)$$

$$B_1 = a_0 + a_1 \cos u + a_2 \cos 2u + \&c. + \beta_1 \sin u + \beta_2 \sin 2u + \&c. \quad (13)$$

We find by means of (9), (10), and (11) the following values :—

TABLE III.—(A_1).

a_0. inches.	a_1. inches.	b_1. inches.
−12·0	+7·8	−1·2
−12·1	+7·7	−1·2
−11·9	+8·0	−1·1
−11·7	+8·3	−0·7
−11·4	+8·7	−0·1
−11·2	+8·3	+0·3
−11·5	+8·7	−0·2
−11·7	+9·0	−0·3
−11·9	+9·5	−0·3
Mean −11·7	+8·4	−0·5

TABLE IV.—(B_1).

a_0. inches.	a_1. inches.	β_1. inches.
−13·4	+1·3	+7·5
−13·5	+1·1	+7·5
−13·2	+1·6	+7·8
−13·3	+1·6	+7·7
−13·3	+1·6	+7·7
−13·2	+1·5	+7·9
−13·0	+1·3	+8·2
−12·7	+0·8	+8·4
−13·1	+1·7	+8·4
Mean −13·2	+1·4	+8·0

The foregoing Tables show that a very regular Diurnal Tide exists at Port Kennedy. In order to compare the observed Tide with theory, we must compare the observed Tide, viz. :—

$$\begin{aligned} &A_1 \cos s + B_1 \sin s \\ &= a_0 + \{a_1 \cos u + b_1 \sin u\} \cos s \\ &+ a_0 + \{a_1 \cos u + \beta_1 \sin u\} \sin s \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14) \end{aligned}$$

with the theoretical Diurnal Tide, viz. :—

$$M' \cos (m - i_m) + S' \cos (s - i_s) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

where

$$M' = M\left(\frac{p}{p_m}\right)^3 \sin \overline{2\mu}$$

$$S' = S\left(\frac{P}{P_m}\right)^3 \sin \overline{2\sigma}$$

M = Lunar Coefficient,
S = Solar Coefficient,
p, p_m = Lunar parallax, Lunar mean parallax,
P, P_m = Solar parallax, Solar mean parallax,
$\overline{\mu}$ = Lunar declination, for a period preceding the time of observation by an interval called the Age of the Lunar Tide—
$\overline{\sigma}$ = Solar declination, for a period preceding the time of observation by an interval called the Age of the Solar Tide—
s = Sun's hour angle,
m = Moon's hour angle,
i_s = Solitidal interval,
i_m = Lunitidal interval.

In order to compare (15) with (14), we must transform (15) into a function of s and u. This may be accomplished as follows:—

Writing

$$m = s + m - s$$

we have

$$m - i_m = s + \overline{m - s - i_m}$$

from which (15) becomes

$$\begin{aligned} &M' \cos (m - i_m) + S' (\cos s - i_s) \\ &= \{M' \cos \overline{m - s - i_m} + S' \cos i_s\} \cos s \\ &\quad \{-M' \sin \overline{m - s - i_m} + S' \sin i_s\} \sin s \quad \ldots\ldots\ldots \quad (16) \end{aligned}$$

From which we obtain, by comparison with (14)

$$A_1 = M' \cos \overline{m - s - i_m} + S' \cos i_s \quad \ldots\ldots\ldots \quad (17)$$

$$B_1 = -M' \sin \overline{m - s - i_m} + S' \sin i_s \quad \ldots\ldots\ldots \quad (18)$$

Having thus got rid of s, we must transform (17) and (18) (which are now functions of $m - s$, and of the Moon's declination, and parallax) into functions of u. This may be thus effected—

1°. We have

$$\frac{p}{p_m} = \frac{a}{r} = \frac{1 + e \cos v}{1 - e^2} \quad \ldots\ldots\ldots \quad (19)$$

where

r = Moon's distance
a = Moon's mean distance
e = Eccentricity of Moon's orbit
v = True anomaly, measured from perigee;

but, by SETH WARD's hypothesis,* we have, also

$$2a-r=\frac{a(1-e^2)}{1-e\cos(nt)}$$

where (nt) is the mean anomaly, measured from perigee. From this we find,

$$\frac{p}{p_m}=\frac{a}{r}=\frac{1-e\cos(nt)}{1-2e\cos(nt)+e^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

hence we find

$$\left(\frac{p}{p_m}\right)^3=\left(1-\frac{e^3}{2}\right)-e\cos(nt)+\frac{e^2}{2}\cos(2nt)+\&c. \quad . \quad . \quad . \quad . \quad . \quad (21)$$

Substituting for e in this equation, its value $\frac{1}{10}$, we obtain

$$\left(\frac{p}{p_m}\right)^3=0{\cdot}999-0{\cdot}05\cos(nt)+0{\cdot}0012\cos(2nt) \quad . \quad . \quad . \quad . \quad . \quad (22)$$

2°. We have, also,

$$\sin 2\mu=2\sin\mu\cos\mu$$

$$=2\sin I\sin(v-n)\sqrt{1-\sin^2 I\sin^2(v-n)}$$

where v is reckoned from perigee, and n is the interval from perigee to the ascending node of the moon's orbit with the equinoctial, and $I=27°\ 40'$, is the inclination of the moon's orbit to the equinoctial.

Hence we find, since $\sin I=0{\cdot}464$

$$\sin 2\mu=2\sin I\sin(v-n)\left[\begin{array}{l}1-\frac{1}{2}\sin^2 I\sin^2(v-n)\\ \quad -\frac{1}{8}\sin^4 I\sin^4(v-n)+\&c. \quad . \quad .\end{array}\right. \quad (23)$$

$$\mathrm{Sin}\ 2\mu=0{\cdot}89\sin(v-n)+0{\cdot}012\sin 3(v-n)+\&c. \quad . \quad . \quad . \quad . \quad (24)$$

The perigee occurred July, $1^d\ 0^h$, and the ascending node, $19^d\ 17^h$; hence $n=18^d\ 17^h=247°$.

Substituting this value of n, we find

$$\sin 2\mu=-0{\cdot}35\sin v+0{\cdot}82\cos v+0{\cdot}01\sin 3v$$
$$-0{\cdot}004\cos 3v+\&c. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

By the well known expansion of the true anomaly in terms of the mean anomaly, we have

* This hypothesis, according to which the angular motion of the revolving body about the focus in which the central body is not, is uniform, is mentioned by Bishop BERKELEY ('Astronomy,' p. 155 of 1st edition) under the title of the *Simple Elliptic Hypothesis*, and was much in use between the times of KEPLER and NEWTON.

$$v=nt+\left(2e-\frac{e^3}{4}\right)\sin(nt)+\frac{5e^2}{4}\sin(2nt)$$
$$+\frac{13}{12}e^3\sin(3nt)+\&c. \quad \ldots\ldots\ldots\ldots \quad (25)$$

Substituting this value in (24) and using the common expansions,

$$\cos x=1-\frac{x^2}{1\cdot2}+\frac{x^4}{1\cdot2\cdot3\cdot4}-\&c.$$

$$\sin x=x-\frac{x^3}{1\cdot2\cdot3}+\&c.$$

we find

$$\sin 2\mu=-0\cdot04-0\cdot35\sin(nt)-0\cdot02\sin(2nt)$$
$$+0\cdot82\cos nt+0\cdot04\cos 2nt+\&c. \quad \ldots\ldots \quad (25)$$

Multiplying together (22) and (25) we find

$$\mathrm{M}'=\mathrm{M}\left(\frac{p}{p_m}\right)^3\sin 2\mu$$
$$=\mathrm{M}(-0\cdot06+0\cdot82\cos nt+0\cdot02\cos 2nt$$
$$-0\cdot35\sin nt-0\cdot01\sin 2nt+\&c. \quad \ldots\ldots\ldots \quad (26)$$

3°. We have now to find values in terms of nt for $\cos\overline{m-s-i_m}$ and $\sin\overline{m-s-i_m}$. This may be done as follows:—

$$m=+kt-m'$$
$$s=+kt-s'$$

where kt is the angle due to the rotation of the earth, and m', s', are the proper motions in right ascension of the moon and sun; therefore

$$m-s=s'-m'$$

We may find m' in terms of v, as follows:—If n be the angle between perigee and ascending node, and c be the angle between conjunction and ascending node, we have

$$\tan(m'-c)=\cos\mathrm{I}\tan(v-n)$$
$$\cos(m'-c)=\frac{1}{\sqrt{1+\cos^2\mathrm{I}\tan^2(v-n)}}$$
$$\sin(m'-c)=\frac{\cos\mathrm{I}\tan(v-n)}{\sqrt{1+\cos^2\mathrm{I}\tan^2(v-n)}}$$

or

$$\cos(m'-c)=\frac{\cos(v-n)}{\sqrt{1-\sin^2\mathrm{I}\sin^2(v-n)}}$$
$$\sin(m'-c)=\frac{\cos\mathrm{I}\sin(v-n)}{\sqrt{1-\sin^2\mathrm{I}\sin^2(v-n)}} \quad \ldots\ldots\ldots \quad (27)$$

or

$$\cos(m'-c)=\cos(v-n)\times \left|\begin{array}{l} 1+0{\cdot}108\sin^2(v-n) \\ +0{\cdot}017\sin^4(v-n) \\ +\&c. \end{array}\right.$$

$$\sin(m'-c)=0{\cdot}886\sin(v-n)\times \left|\begin{array}{l} 1+0{\cdot}108\sin^2(v-n) \\ +0{\cdot}017\sin^4(v-n) \\ +\&c. \end{array}\right. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

From these equations we have, remembering that

$$n=247^\circ$$
$$\cos(m'-c)=-0{\cdot}42\cos v-0{\cdot}99\sin v+\&c.$$
$$\sin(m'-c)=+0{\cdot}85\cos v-0{\cdot}36\sin v+\&c. \quad . \quad . \quad . \quad . \quad . \quad (29)$$

We now have—

$$\cos(m-s-i_m)=\cos(s'-m'-i_m)$$
$$=\cos\{(-m'+c)+(-c+s'-i_m)\}$$
$$=\cos(-m'+c+\phi)$$
where $\phi=-c+s'-i_m$.

Expanding and substituting from (29) we find

$$\cos(m-s-i_m)$$
$$\{-0{\cdot}42\cos\phi+0{\cdot}85\sin\phi\}\cos v$$
$$+\{-0{\cdot}99\cos\phi-0{\cdot}36\sin\phi\}\sin v \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

In like manner we have

$$\sin(m-s-i_m)=$$
$$\{-0{\cdot}85\cos\phi-0{\cdot}42\sin\phi\}\cos v$$
$$+\{+0{\cdot}36\cos\phi-0{\cdot}99\sin\phi\}\sin v \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

Substituting in (30) and (31), for v, its value $v=nt+2e\sin nt$ (25),

we obtain, writing $\left|\begin{array}{l} A=-0{\cdot}42\cos\phi+0{\cdot}85\sin\phi \\ B=-0{\cdot}99\cos\phi-0{\cdot}36\sin\phi \end{array}\right.$

$$\cos(m-s-i_m)=$$
$$-Ae+A\cos nt+Ae\cos 2nt+\&c.$$
$$+B\sin nt+Be\sin 2nt+\&c. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

$$\sin(m-s-i_m)=$$
$$-A'e+A'\cos nt+Ae\cos 2nt+\&c.$$
$$+B'\sin nt+B'e\sin 2nt+\&c. \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

where

$$A'=-0{\cdot}85\cos\phi-0{\cdot}42\sin\phi$$
$$B'=+0{\cdot}36\cos\phi-0{\cdot}99\sin\phi$$

Multiplying together (26) and (32), we have, as a first approximation

$$\begin{aligned} M' \cos \overline{m-s-i_m} = & \\ & (0{\cdot}41A - 0{\cdot}18B) + (0{\cdot}41A + 0{\cdot}18B) \cos 2nt \\ & \qquad (-0{\cdot}18A + 0{\cdot}41B) \sin 2nt \end{aligned}$$

or,

$$\begin{aligned} M' \cos (m-s-i_m) = & + 0{\cdot}33M \sin \phi \\ & + M\,(-0{\cdot}35 \cos \phi + 0{\cdot}29 \sin \phi) \cos 2nt \\ & + M\,(-0{\cdot}34 \cos \phi + 0{\cdot}30 \sin \phi) \sin 2nt \quad \ldots\ldots\ldots \quad (34) \end{aligned}$$

Multiplying together (26) and (33) we find, also,

$$\begin{aligned} M' \sin \overline{(m-s-i_m)} = & \\ & (0{\cdot}42A' - 0{\cdot}18B') + (0{\cdot}42A' + 0{\cdot}18B') \cos 2nt \\ & \qquad + (-0{\cdot}18A' + 0{\cdot}42B') \sin 2nt \end{aligned}$$

or,

$$\begin{aligned} M' \sin \overline{(m-s-i_m)} = & - 0{\cdot}41M \cos \phi \\ & + M\,(-0{\cdot}30 \cos \phi - 0{\cdot}35 \sin \phi) \cos 2nt \\ & + M\,(+0{\cdot}30 \cos \phi - 0{\cdot}34 \sin \phi) \sin 2nt \quad \ldots\ldots\ldots \quad (35) \end{aligned}$$

Equations (34) and (35) are now to be converted into functions of u, which may be effected, in general, by means of the following expansions,* in which a is a proper fraction :—

$$\cos a x = \frac{\sin a\pi}{\pi} \left[\frac{1}{a} + 2a \left[\begin{array}{l} \dfrac{\cos x}{1^2 - a^2} \\ -\dfrac{\cos 2x}{2^2 - a^2} \\ +\dfrac{\cos 3x}{3^2 - a^2} \\ -\dfrac{\cos 4x}{4^2 - a^2} \\ +\&c. \end{array} \right. \right. \quad \ldots\ldots\ldots \quad (36)$$

$$\sin a x = \frac{2 \sin a\pi}{\pi} \left[\begin{array}{l} \dfrac{\sin x}{1^2 - a^2} \\ -\dfrac{2 \sin 2x}{2^2 - a^2} \\ +\dfrac{3 \sin 3x}{3^2 - a^2} \\ -\dfrac{4 \sin 4x}{4^2 - a^2} \\ +\&c. \end{array} \right. \quad \ldots\ldots\ldots \quad (37)$$

* I am indebted to Benjamin Williamson, F.T.C.D., for these formulæ.

Let us now proceed to express (20) and (21) in terms of u,

$$\left(\frac{p}{p_m}\right)^2 = 2{\cdot}35 + 4{\cdot}57\cos v + 0{\cdot}45\cos 2v \quad (20)$$

neglecting smaller terms, and v is reckoned from Perigee, which occurred at noon, on 1st July.

The angle $u=0$ at midnight of July 12th, and $nt=0$ at Perigee at noon of July 1st.

$u=0$, at July		12^d	12^h
$nt=0$	,,	1	0
	Diff.	11^d	12^h

This is equivalent to 152°, since the periodic time is 27·3 days.

Hence we have

$$nt - 152° = \frac{140}{273}u$$

$$2nt = 304° + \frac{280}{273}u$$

Substituting this value in (34) and (35) we obtain

$$\begin{aligned} M'\cos(m-s-i_m) &= +0{\cdot}41\,M\sin\phi \\ &+ M\left(-0{\cdot}35\cos\phi + 0{\cdot}29\sin\phi\right)\cos\left(\frac{280}{273}u\right) \\ &+ M\left(-0{\cdot}34\cos\phi - 0{\cdot}30\sin\phi\right)\sin\left(\frac{280}{273}u\right) \quad \ldots\ldots\ldots \quad (38) \end{aligned}$$

$$\begin{aligned} M'\sin(m-s-i_m) &= -0{\cdot}41\,M\cos\phi) \\ &+ M\left(-0{\cdot}30\cos\phi - 0{\cdot}35\sin\phi\right)\cos\left(\frac{280}{273}u\right) \\ &+ M\left(0{\cdot}30\cos\phi - 0{\cdot}34\sin\phi\right)\sin\left(\frac{280}{273}u\right) \quad \ldots\ldots\ldots \quad (39) \end{aligned}$$

As a first approximation, $\frac{280}{273}u$ may be made equal to u, and afterwards, if necessary, the expansions (36) and (37) employed.

Equations (17) and (18) give us

$$\begin{aligned} A_1 &= M'\cos(m-s-i_m) + S\cos 2\sigma\cos i, \\ B_1 &= -M'\sin(m-s-i_m) + S\cos 2\sigma\sin i, \end{aligned}$$

or, since $\sigma=22°$, when $u=0$, on 12th July, 1859,

$$\begin{aligned} A_1 &= M'\cos(m-s-i_m) + 0{\cdot}69S\cos i, \\ B_1 &= -M'\sin(m-s-i_m) + 0{\cdot}69S\sin i, \end{aligned}$$

or, from (38) and (39),

$$\begin{aligned} A_1 = &\{0{\cdot}69S\cos i_s + 0{\cdot}41M\sin\phi\} \\ &+M\{-0{\cdot}35\cos\phi + 0{\cdot}29\sin\phi\}\cos u \\ &+M\{-0{\cdot}34\cos\phi - 0{\cdot}30\sin\phi\}\sin u \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (40) \end{aligned}$$

$$\begin{aligned} B_1 = &\{0{\cdot}69S\sin i_s - 0{\cdot}41M\cos\phi\} \\ &+M\{0{\cdot}30\cos\phi + 0{\cdot}35\sin\phi\}\cos u \\ &+M\{-0{\cdot}30\cos\phi + 0{\cdot}34\sin\phi\}\sin u \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (41) \end{aligned}$$

We have, therefore, from Tables III. and IV.,

$$\begin{aligned} 0{\cdot}69S\cos i_s + 0{\cdot}41M\sin\phi &= -11{\cdot}7 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a) \\ M(-0{\cdot}35\cos\phi + 0{\cdot}29\sin\phi) &= +8{\cdot}4 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (b) \\ M(-0{\cdot}34\cos\phi - 0{\cdot}30\sin\phi) &= -0{\cdot}5 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (c) \\ 0{\cdot}69S\sin i_s - 0{\cdot}41M\cos\phi &= -13{\cdot}2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (d) \\ +M(0{\cdot}30\cos\phi + 0{\cdot}35\sin\phi) &= +1{\cdot}4 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (e) \\ +M(-0{\cdot}30\cos\phi + 0{\cdot}34\sin\phi) &= +8{\cdot}0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (f) \end{aligned}$$

From (b) and (c) we find

$$M = 19{\cdot}4 \text{ inches}, \quad \phi = 128^\circ\ 5',$$

choosing that value of ϕ which makes M positive in the equations (b) and (c).

From (e) and (f) we find

$$M = 17{\cdot}6 \text{ inches}, \quad \phi = 129^\circ\ 30'.$$

These values of M and ϕ agree very well, and taking means, we have

$$\begin{aligned} M &= 18{\cdot}5 \text{ inches} \\ \phi &= 128^\circ\ 48' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (42) \end{aligned}$$

but

$$\phi = -c + s' - i_m,$$

and Conjunction happened at June $29^d\ 0^h$
and ascending node . . . July $19^d\ 17^h$

Diff. $20^d{\cdot}7$

Hence

$$c = \frac{20{\cdot}7 \times 360}{29{\cdot}5} = 252^\circ\ 30'$$

and s' increases at the rate of a degree per day, or $s' = 20^\circ\ 42'$.

Therefore

$$\begin{aligned} i_m &= -c + s' - \phi \\ &= -360^\circ\ 36' = -0^\circ\ 36' \end{aligned}$$

or, converting the arc into time

$$i_m = -2^m{\cdot}48 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (43)$$

From (*a*) and (*d*) we obtain

$$0{\cdot}69\mathrm{S}\cos i_s + 0{\cdot}41\mathrm{M}\sin\phi = -11{\cdot}7 \quad (a)$$
$$0{\cdot}69\mathrm{S}\sin i_s - 0{\cdot}41\mathrm{M}\cos\phi = -13{\cdot}2 \quad (d)$$

Introducing the mean values of M and ϕ, (42) we find

$$\mathrm{S} = 36{\cdot}4 \text{ inches}$$
$$i_s = 45^\circ\ 26' = 3^h\ 2^m \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

We thus find, finally, from the present and former calculations,

Diurnal Tidal Constants.

I. Hourly Observations.	*II. High and Low Water Observations.*
M = 18·5 inches	M = 20·9 inches
$i_m = -2^m{\cdot}48$	$i_m = +38^m{\cdot}8$
S = 36·4 inches	S = 23·4 inches
$i_s = +3^h\ 2^m$	$i_s = +5^h\ 12^m$

From the preceding values, it is evident, that the present more complete investigation fully confirms my former conclusion, as to the unusually great magnitude of the Solar Diurnal Tide at Port Kennedy.

III. *Semidiurnal Tide.*

We must now calculate the values of A_2 and B_2 from the equations (9–14). We thus obtain

TABLE V.—(A_2).

a_0 inches.	a_1 inches.	b_1 inches.
+2·9	−16·3	− 9·3
+3·7	−14·7	− 9·3
+4·2	−13·8	− 8·9
+4·4	−13·5	− 8·5
+4·1	−13·7	− 9·2
+3·4	−13·4	−10·6
+2·8	−12·7	−10·5
+1·5	−11·8	−12·6
+1·1	− 9·6	−12·6
Mean +3·1	−13·3	−10·2

TABLE VI.—(B_3).

α_0 inches.	α_1 inches.	β_1 inches.
+3·6	+ 5·2	−15·2
+4·1	+ 6·3	−15·2
+5·1	+ 8·0	−14·3
+6·2	+ 9·5	−12·4
+7·2	+ 9·9	− 9·2
+7·5	+ 9·8	−10·8
+7·0	+10·4	−10·7
+6·4	+11·5	−11·2
+6·8	+12·9	−11·2
Mean+6·0	+ 8·2	−12·2

These results are to be compared with the expansion of the formula for the Semi-diurnal Tide, viz.

$$M' \cos 2(m-i_m) + S' \cos 2(s-i_s) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

from which we obtain as before, writing

$$m = s+m-s$$
$$A_3 = M' \cos 2(m-s-i_m) + S' \cos 2i_s$$
$$B_3 = M' \sin 2(m-s-i_m) + S' \sin 2i_s \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (46)$$

where

$$M' = M\left(\frac{p}{p_m}\right)^3 \cos^3 \bar{\mu}$$
$$S' = S\left(\frac{p}{p_m}\right)^3 \cos^3 \bar{\sigma} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

Neglecting the eccentricity of the Lunar Orbit, for a first approximation, we have

$$M' = M(\cos^3 \mu = M(1-\sin^2 1 \sin^2 (v-n))$$
$$= M(1-0{\cdot}215 \sin^2 (v-n))$$
$$= M(0{\cdot}89+0{\cdot}11 \cos 2(v-n))$$

or since $n=247°$,

$$M' = M(0{\cdot}89-0{\cdot}76 \cos 2v+0{\cdot}79 \sin 2v) \quad . \quad . \quad . \quad . \quad . \quad . \quad (48)$$

We have also

$$2(m-s)-2i_m = -2(m'-s')-2i_m$$
$$= -2(m'-c)+2(s'-c-i_m)$$
$$= -2(m'-c)+2\phi$$

where as before

$$\phi = s'-c-i_m \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (49)$$

From (29) we find

$$\begin{aligned}\cos(2m'-c) &= +0{\cdot}16-0{\cdot}71\cos 2v \\ &\quad +0{\cdot}72\sin 2v \\ \sin 2(m'-c) &= -0{\cdot}72\cos 2v-0{\cdot}69\sin 2v \quad \ldots\ldots (50)\end{aligned}$$

Hence we find

$$\begin{aligned}\cos 2(m-s-i_m) &= \cos 2(-(m'-c)+\phi) \\ &= 0{\cdot}16\cos 2\phi-\{0{\cdot}71\cos 2\phi-0{\cdot}72\sin 2\phi\}\cos 2v \\ &\quad +\{0{\cdot}72\cos 2\phi-0{\cdot}69\sin 2\phi\}\sin 2v \quad \ldots\ldots (51) \\ \sin 2(m-s-i_m) &= \sin 2(-(m'-c)+\phi) \\ &= 0{\cdot}16\sin 2\phi+\{0{\cdot}72\cos 2\phi-0{\cdot}71\sin 2\phi\}\cos 2v \\ &\quad +\{0{\cdot}69\cos 2\phi+0{\cdot}72\sin 2\phi\}\sin 2v\end{aligned}$$

If we make $v=u$ (as an approximation) in (48) and (51), we find writing

$$\begin{aligned}A &= 0{\cdot}71\cos 2\phi+0{\cdot}72\sin 2\phi \\ B &= 0{\cdot}72\cos 2\phi-0{\cdot}69\sin 2\phi \\ A' &= 0{\cdot}72\cos 2\phi-0{\cdot}69\sin 2\phi \\ B' &= 0{\cdot}69\cos 2\phi+0{\cdot}72\sin 2\phi \quad \ldots\ldots\ldots (52)\end{aligned}$$

$$\begin{aligned}M'\cos 2(m-s-i_m) &= M\begin{pmatrix}0{\cdot}14\cos 2\phi \\ +0{\cdot}38A+0{\cdot}40B\end{pmatrix} \\ &\quad -M\{0{\cdot}89A+0{\cdot}12\cos 2\phi\}\cos 2v \\ &\quad +M\{0{\cdot}89B+0{\cdot}12\cos 2\phi\}\sin 2v+\&c. \\ M'\sin 2(m-s-i_m) &= M\begin{pmatrix}0{\cdot}14\sin 2\phi \\ -0{\cdot}38A'+0{\cdot}40B'\end{pmatrix} \quad \ldots\ldots (52) \\ &\quad +M\{0{\cdot}89A'-0{\cdot}12\sin 2\phi\}\cos 2v \\ &\quad +M\{0{\cdot}89B'+0{\cdot}12\sin 2\phi\}\sin 2v+\&c.\end{aligned}$$

Hence, from (46), since $S'=S\cos 2\sigma$, and $\sigma=22°$, we find

$$\begin{aligned}A_1 &= M\{0{\cdot}14\cos 2\phi+0{\cdot}38A+0{\cdot}40B\}+0{\cdot}86S\cos 2i, \\ &\quad -M\{0{\cdot}89A+0{\cdot}12\cos 2\phi\}\cos 2v \\ &\quad +M\{0{\cdot}89B+0{\cdot}12\cos 2\phi\}\sin 2v+\&c. \\ B_1 &= M\{-0{\cdot}14\sin 2\phi+0{\cdot}38A'-0{\cdot}40B'\}+0{\cdot}86\,S\sin 2i, \\ &\quad -M\{0{\cdot}89A'-0{\cdot}12\sin 2\phi\}\cos 2v \\ &\quad -M\{0{\cdot}89B'+0{\cdot}12\sin 2\phi\}\sin 2v+\&c.\end{aligned}$$

Comparing these expansions with Tables V. and VI. we find

$$\begin{aligned}M\{0{\cdot}14\cos 2\phi+0{\cdot}38\,A+0{\cdot}40\,B\}+0{\cdot}86\,S\cos 2i, &= 3{\cdot}1 \quad \ldots (a') \\ M\{0{\cdot}89\,A+0{\cdot}12\cos 2\phi\} &= 13{\cdot}3 \quad \ldots\ldots (b') \\ M\{0{\cdot}89\,B+0{\cdot}12\cos 2\phi\} &= -10{\cdot}2 \quad \ldots\ldots (c') \\ M\{-0{\cdot}14\sin 2\phi+0{\cdot}38\,A'-0{\cdot}40\,B'\}+0{\cdot}86\,S\sin 2i, &= 6{\cdot}0 \quad \ldots (d') \\ M\{-0{\cdot}89\,A'-0{\cdot}12\sin 2\phi\} &= -8{\cdot}2 \quad \ldots\ldots (e') \\ M\{0{\cdot}89\,B'+0{\cdot}12\sin 2\phi\} &= 12{\cdot}2 \quad \ldots\ldots (f')\end{aligned}$$

Substituting, in these equations, the values of A, B, A′, B′, we find

$$0{\cdot}60\,M\cos 2\phi + 0{\cdot}86\,S\cos i_s = 3{\cdot}1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (a')$$
$$M\,(0{\cdot}75\cos 2\phi + 0{\cdot}64\sin 2\phi) = 13{\cdot}3 \quad . \quad . \quad . \quad . \quad . \quad (b')$$
$$M\,(0{\cdot}76\cos 2\phi - 0{\cdot}61\sin 2\phi) = -10{\cdot}2 \quad . \quad . \quad . \quad . \quad . \quad (c')$$
$$-0{\cdot}60\,M\sin 2\phi + 0{\cdot}86\,S\sin i_s = 6{\cdot}0 \quad . \quad . \quad . \quad . \quad . \quad (d')$$
$$M\,(0{\cdot}64\cos 2\phi - 0{\cdot}75\sin 2\phi = -8{\cdot}2 \quad . \quad . \quad . \quad . \quad . \quad (e')$$
$$M\,(0{\cdot}61\cos 2\phi + 0{\cdot}76\sin 2\phi) = 12{\cdot}2 \quad . \quad . \quad . \quad . \quad . \quad (f') \qquad (53)$$

From (b') and (c') we find, remembering that M must be positive,

$$2\phi = 84^\circ\ 48',\quad M = 19{\cdot}0 \text{ inches}$$

and from (d') and (f') we find

$$2\phi = 77^\circ\ 10',\quad M = 14{\cdot}0 \text{ inches.}$$

Mean values

$$2\phi = 80^\circ\ 59',\quad M = 15{\cdot}5 \text{ inches.} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (54)$$

Hence we find, since,

$$i_m = s' - c - \phi,$$

using the values of s' and c already given,

$$i_m = 87^\circ\ 42' = 6^h\ 2^m\ 5^s \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (55)$$

From (a') and (d') we find, using the mean values of M and 2ϕ,

$$S = 5{\cdot}9 \text{ inches.} \qquad i_s = 41^\circ\ 55' = 2^h\ 48^m \quad . \quad . \quad . \quad . \quad . \qquad (56)$$

We thus find, finally, from the present and former calculations,

Semidiurnal Tidal Constants.

I.—*Hourly Observations.*	II.—*H. and L. W. Observations.*
$M = 15{\cdot}5$ inches	$M = 17{\cdot}0$ inches
$i_m = 6^h\ 2^m\frac{1}{2}$	$i_m = 23^h\ 48^m$
$S = 5{\cdot}9$ inches	$S = 7{\cdot}0$ inches
$i_s = 2^h\ 48^m$	$i' =$ ——
$\frac{S}{M} = 0{\cdot}39$	$\frac{S}{M} = 0{\cdot}41$

II. *Electrostatic Capacity of Glass.*

By J. Hopkinson, *D.Sc., M.A.*
Communicated by Sir William Thomson, *F.R.S.*

Received May 17,—Read June 14, 1877.

[Plate 2.]

1. In his work on Electricity and Magnetism Professor Maxwell developes a theory in which electric and magnetic phenomena are explained by changes of position of the medium, the wave motion of which constitutes Light. He deduces with the aid of this theory that that velocity, which is the ratio of the electrostatic and electromagnetic units of electric quantity, is identical with the velocity of light. This deduction may be said to be verified within the limits of error of our knowledge of these quantities. He further finds that the product of the electrostatic capacity and the magnetic permeability of a transparent substance is equal to the square of the refractive index for long waves. The only available experiments for testing this result when Professor Maxwell's book was published* were the "Determinations of Electrostatic Capacity of Solid Paraffin," by Messrs. Gibson and Barclay (Phil. Trans., 1871), and the 'Determinations of Refractive Indices of Melted Paraffin,' by Dr. Gladstone. Considering the difference in physical state in the two experiments the result verifies the theory fairly well. The various kinds of optical flint glass are suitable for the purpose of making a comparison of refractive indices and specific inductive capacity, since each is an article pretty constant in its composition and physical properties, and has small conductivity and return charge.

2. The only convenient form in which glass can be examined is a plate with plane parallel sides; this plate must form the dielectric of a guard ring condenser. Four instruments are thus required, the guard ring condenser, an adjustable condenser which can be made equal to the first, a battery for giving equal and opposite charges to the two condensers, and an electroscope to show when the added charges of the condensers are nil.

Guard Ring Condenser.—Fig. (1) represents the guard ring condenser in elevation;

* Since then determinations have been made by Boltzmann for paraffin, colophonium, and sulphur (Pogg. Annalen, 1874, vol. cli. pp. 482 and 531, and vol. cliii. p. 525), and for various gases (Pogg. Ann., 1875, vol. clv. p. 403), by Silow for oil of turpentine and petroleum (Pogg. Ann., 1875, vol. clvi. p. 389, and 1876, vol. clviii. p. 306), and by Schiller (Pogg. Ann., 1874, vol. cli. p. 535) and Wüllner (Pogg. Ann., 1877, new series, vol. i. pp. 247, 361) for plate glass.

fig. (2) in plan through *h h*. It consists essentially of an insulated brass disc *k* surrounded by a flat ring *h h*, and covered by a brass shield connected with *h h*. It is opposed by a larger disc *e e* parallel with *k* and *h h*, which is always connected to the case of the electrometer. The disc *k* and ring *h h* are connected, simultaneously charged, next separated, and then at one moment *h* is put to earth, and *k* discharged in such manner as the experiment may require.

a b and *c d* are triangular pieces of iron forming with three wrought-iron stays a stiff frame. To the tops of these stays are screwed three legs of ebonite *g g*, which serve to support and insulate the guard ring *h h*. The disc *e e* is of brass truly turned, it is carried on a stem which is screwed for a portion of its length with exactly 25 threads to the inch, a motion parallel to itself is secured by bearings in each frame plate; these are not ordinary round bearings which may work loose, but are of the form represented full size in fig. 3. *e e* is prevented from rotating by a pin working through a hole in the upper triangular plate and pressed against one side of the hole by a steel spring. The plate *e e* is raised or lowered by a milled nut *f*, divided on the circumference into 100 parts, and bearing upon a piece of brass tubing secured to the lower plate of the frame. *k* is carried by two rods of ebonite *l l*, which insulate it from *h h*; both were faced in the lathe together so as to be truly in one plane. The diameter of the disc *k* is 150 millims., it is separated from the ring by a space of 1 millim. When the capacity of a glass plate is to be measured a dish of pumice and sulphuric acid is placed upon the disc *k* between the rods *l l*, and a second dish upon the triangular plate *c d*, the whole instrument being loosely surrounded by a glass cylinder. This instrument also serves to measure with sufficient accuracy the thickness of the glass plates. To ascertain when the plates are in contact, or when the glass plate to be measured is in contact with *h k h*, slips of tissue paper are interposed between the ebonite legs *g g* and the plate *h h*, and the contact is judged by these slips becoming loose, a reading being taken for each slip.

The sliding condenser was the identical instrument used by Gibson and Barclay, kindly lent to the author by Sir W. Thomson; it was used simply as a variable condenser. Although a more finely graduated instrument than the guard ring condenser, it was not used as a measuring instrument, because its zero readings had to be valued by the guard ring condenser; it seemed better to use it like the counterpoise in the system of double weighing, adjusting it to the guard ring condenser with the glass in, then removing the glass and adjusting the guard ring condenser to equality with the sliding condenser. It suffices to say that the sliding condenser has two adjustments, a fine one denoted here by S_1, and a coarse one denoted by S_2.

The electroscope was Sir W. Thomson's quadrant electrometer adjusted for maximum sensibility and charged as highly as it would stand. A single Daniell's element gave from 120 to 160 divisions of the scale.

The battery consisted of 48 or of 72 DANIELL's elements of a very simple construction; a piece of copper wire covered with gutta percha is stripped for a short distance at each end, it is set in a test tube 6 or 7 inches long, a piece of zinc being soldered to its upper extremity. Some sulphate of copper in powder is put in the tube around the exposed wire, this is covered by a thick plug of plaster of Paris, and the element completed by the addition of dilute zinc sulphate solution, into which the zinc which is soldered to the wire of the next element dips. The element has a very high resistance, but that is of no consequence for electrostatic experiments. The middle of the series is put to earth. The battery thus gives the means of charging two condensers to equal but opposite potentials. The poles of the battery are connected with the switch through the electrometer reversing key. In each case two experiments are made, one in which the guard ring is positive, in the other negative.

The switch is represented in plan in fig. 4, and its place is indicated in elevation in fig. 1. Calling the poles of the battery A and B, its purpose is to make rapidly the following changes of connection :—

(1.) A, sliding condenser; B, guard ring, disc k; earth, quadrant of electrometer.

(2.) A, B, guard ring, earth; disc k, sliding condenser.

(3.) To connect the disc k and the sliding condenser to the quadrant of the electrometer.

The combination (1) may exist for any time long or short, but (3) follows (2) within a fraction of a second, and the observation of the electroscope consists in deciding whether or not the image moves *at the instant* of combination (3), and, if it moves, in which direction. In (2) the poles of the battery are put to earth, in order that one may be sure that the parts of the switch with which they are connected do not disturb the result by inductive action on the parts connected with the condensers.

$q\ q$ is a plate of ebonite screwed to the shielding cover of the condenser, r is a steel spring connected to earth, s a similar steel spring connected to one pole of the battery.

$t\ v$ are segments of brass of which the securing screws pass through to the brass cover.

$w\ u$, similar segments insulated from the brass cover and guard ring, connected respectively to the sliding condenser and the electrometer.

p is an ebonite handle and brass pin which turns in an insulated brass socket connected by a spring m with the disc k; p carries a piece of ebonite $x\ x$ which moves the springs $r\ s$ from contact with $t\ v$ to contact with $u\ w$, and also a spring $y\ y$ which may connect $t\ v$ with the disc k, or, when turned into the position indicated, w with the disc k, and instantly after both with the electrometer. One pole of the battery is always connected to the guard $h\ h$. The switch is protected against inductive action from the hand of the observer, or from electrification of the top of the ebonite handle when touched with the finger by a copper shield $n\ n$ connected with the guard ring through the cover.

The guard ring screw reading is denoted by R. R (+) when the guard ring is positive, R (−) when it is negative. This condenser must be regarded as a circular plate of 151 millims. diameter with a uniform distribution of electricity on its under surface; its capacity is therefore $\frac{140{\cdot}3}{x}$ centimetres where x = R − the reading when k and $e\ e$ are in contact.

3. In order to ascertain the distance between the plates from the screw reading R, it is necessary to know the reading when the plates $k\ h\ h$ and $e\ e$ are in contact. Slips of thin tissue paper are introduced at the top of each of the ebonite legs, the lower plate is raised, and a reading is made when each slip becomes loose; the mean of the three readings may be taken as the zero when the instrument is used to measure the thickness of plates, or when $h\ k\ h$ is carried by an interposed plate, but it will require a correction when in the subsequent measurements the upper plate is carried by the ebonite supports only, for the upper plate must have been lifted by a greater or less amount depending on the compression of the paper slips and on the imperfect rigidity of the brass before the slips can be released. The amount of this correction was estimated in two different ways.

1st. Everything on the upper plate was connected with one pole of the battery and also with the electrometer. The plates were brought to contact; it was found the slips became loose at 1·15, 1·13, 1·09, mean 1·12, the lower plate was very slowly lowered until the upper plate became insulated, as declared by the movement of the image on the electrometer scale. This occurred at 1·22, indicating a correction of 0·10.

2nd. A plate of light flint glass was introduced between the condenser plates; the slips were just loose at readings—

16·15 16·16 16·11. Mean 16·14.

The two condensers were now connected through the switch and rendered equal, the screw being turned to vary the distance of the plates, and the slide being adjusted to make the sliding condenser equal to the guard ring. The following corresponding pairs of readings were obtained:—

R	16·10	16·20	16·30	16·25	16·40
S_1	180	180	150	170	100
R	16·30	16·27	16·24	16·20	16·17
S_1	150	170	180	180	185

It thus appears that the capacity of the guard ring condenser does not begin to diminish till R is between 16·24 and 16·27. This indicates a correction between 0·10 and 0·13. Throughout the experiments a correction of 0·10 is used whenever the upper plate is carried by the ebonite legs alone.

4. The glasses examined were CHANCE'S *optical light flint, double extra dense flint, dense flint, a special light flint*, and a piece of common plate glass.

Light flint, density about 3·2.

Two plates were examined of different thickness, the plates were also from different meltings of glass made at different times, and may be regarded as two quite independent samples of glasses intended to be of the same composition.

A. Thickness, 15·01 turns of the screw; diameter, 220 millims.

First Experiment.—Plates of guard ring condenser in contact with glass plate. 48 elements in the battery.

$S_2=0$ $S_1=50$ when sliding condenser positive.
$=20$ „ „ negative.
Mean $=35$

It is found that $S_2=0$, $S_1=35$ is equal to the guard ring condenser with the glass plate out, when the distance between the plates is 2·18 turns of screw,

Hence $K=6·89$.

Second Experiment.—Battery of 72 elements.

S_2 drawn out beyond the graduation, $S_1=160$ when slide is positive.
$=220$ „ negative.
Mean $=190$

Glass plate removed.

$S_1=190$ R (+)$=3·50$ R (−)$=3·43$.

Mean reading for contact of plates 1·14, when corrected 1·24.
So plate of glass 15·01 is equal to plate of air 2·225,

Hence $K=6·76$.

B. Thickness, 10·75 turns of screw; diameter, 220 millims.

Plates of guard ring both in contact with glass, battery of 72 elements.

$S_2=25$ $S_1=450$ when positive.
$=400$ when negative.

Glass plate removed.

$S_1=425$ equivalent to R (+)$=2·85$
R (−)$=2·80$

or plate of glass 10·75 equal to air 1·585.

$K=6·90$.

Mean of three determinations—

6·85.

"*Double extra dense flint glass*," or "*Triple dense flint*," density about 4·5.
Thickness of plate, 24·27 turns; diameter, 235 millims.

First Experiment.—Plates in contact with glass. 48 elements in battery.

S_2 drawn out, $S_1=95$.

Plate removed, condensers again equal when R=3·60.

Hence K=10·28.

Second Experiment.—Plates in contact with glass. 72 elements in battery.

S_2 drawn out, $S_1=55$ when slide is positive.

$=95$ „ negative.

$S_1=75$ is equivalent to R (−)=3·61

R (+)=3·69

K=10·07.

The latter result is probably much the best; take 10·1 as most probable value.

In the next two glasses the determinations were made first with plates in contact with glass, second with a space of air between the glass and the upper plate; the results suggested the experiments of § 3. In each case 72 elements were used.

Dense flint (the glass generally used in the objectives of telescopes).—Density about 3·66, thickness =16·58 turns of the screw, diameter =230 millims.

First Experiment.—Plates in contact with glass, S_2 drawn out.

When the slide is positive, $S_1=205$, on removal of glass plate this equals R (−)=5·50. When the slide is negative, $S_1=175$, on removal of glass plate R (+)=3·50.

Hence K=7·34.

The mean zero reading being now 1·15.

Second Experiment.—R is put at 18·14 with glass between the plates.

S_2 drawn out when the slide is negative.

$S_1=10$ on removing glass equals R (+) 3·78, when the slide is positive.

$S_2=40$ on removing glass equals R (−) 3·79, *i.e.* glass 16·58 and air 0·32 are equivalent to air 2·525 or K=7·45.

Mean=7·4.

A very light flint.—Density about 2·87, thickness =12·7 turns of the screw, diameter =235 millims.

First Experiment.—Plates in contact with glass S_2 drawn out, when the slide is negative.

$S_1=380$ on removing glass equals R (+) 3·20, when the slide is positive.

$S_1=440$ on removing glass equals R (−) 3·18.

K=6·6.

Second Experiment.—R was put at 14·50, S_2 was drawn out when the slide is positive.

$S_1=80$ on removing glass equal to R (−) 3·71, when the slide is negative.

$S_1=50$ on removing glass equal to R (+) 3·72, so glass 12·70 and air 0·55 is equivalent to air 2·475.

$$K=6·55.$$

Mean=6·57.

An attempt was made to determine K for a piece of plate glass; the considerable final conductivity of the glass caused no serious inconvenience, but the very great development of that polarization on which residual charge depends produced a condenser in which the capacity seemed to increase very rapidly indeed during a second or so after making connexions; this effect could not be entirely separated from the instantaneous capacity, a value K=7 was obtained, but it was quite certain that a considerable part of this took time to develope.

5. The repetition of the experiment in each case gives some notion of the probable error of the preceding experiments. Something must be added for the uncertainty of the contact reading. It will perhaps not be rash to assume the results to be true within 2 per cent.

Since the magnetic permeability cannot be supposed to be much less than unity, it follows that these experiments by no means verify the theoretical result obtained by Professor MAXWELL, but it should not be inferred that his theory in its *more general* characters is disproved.

If the electrostatic capacities be divided by the density, we find the following quotients:—

	ρ	K	$\frac{K}{\rho}$	μ (index of refraction for line D)
Light flint	3·2	6·85	2·14	1·574
Double extra dense	4·5	10·1	2·25	1·710
Dense flint	3·66	7·4	2·02	1·622
Very light flint	2·87	6·57	2·29	1·541

Thus $\frac{K}{\rho}$ is not vastly different from a constant quantity. Messrs. GIBSON and BARCLAY find K for paraffin 1·977; taking the density of paraffin as 0·93, we have the quotient 2·13. This empirical result cannot of course be generally true, or the capacity of a substance of small density would be less than unity.

III. *On the Structure and Development of Vascular Dentine.*

By Charles S. Tomes, *M.A.*
Communicated by John Tomes, *F.R.S.*

Received February 6,—Read March 8, 1877.

[Plates 3–5.]

The minute structure and the development of that variety of dentine which is met with in most mammalian teeth, and which goes by the name of hard or unvascular dentine, have been repeatedly and very carefully worked out, and our knowledge of their intimate nature is quite on a par with our knowledge of that of the tissues of other parts of the body. But the intimate structure of those interesting and, from a morphological point of view, important varieties of dentine, known as vaso-dentine and osteo-dentine, is but very imperfectly known; in point of fact, whilst the arrangement of the tubes and channels which permeate their substance has been satisfactorily described by many observers, so far as it can be studied in sections of dried teeth, next to nothing is with any certainty known as to the contents of these channels, nor as to the manner in which they were formed.

In this paper I propose to give the results of a series of observations upon the development of vascular dentine, and the relation which it, in its completed condition, bears to the dental pulp; and I hope to be able to place the nomenclature and classification of the varieties of dentine upon a more satisfactory basis, by bringing them into accordance with the facts elicited by a study of development, which at present they are not.

So far as I can ascertain, although several observers had at an earlier period described the tissue which we know as vaso-dentine, Retzius was the first whose descriptions were accurate, and how accurate they were is attested by the fact that, so far as they go (he having described the hard tissues only), there is now, forty years later, little or nothing to be altered in them. But although Retzius recognized and very carefully described the tissues in question, he did not give to them any distinctive name, and Professor Owen, following in the footsteps of Retzius, introduced the convenient terms vaso-dentine and osteo-dentine, and hence ('Odontography,' p. xvii.) claims to have been the first to characterise vascular-dentine "as a component of tooth, 'distinct from ivory, enamel, cement, and true bone, and as easily recognisable,'" so that Continental writers often speak of the "vaso-dentine" and "osteo-dentine" of Owen. But it should not be forgotten that Retzius, though he did not give a distinctive name,

described these varieties of dentine in the clearest terms. For example, he says, "this form of dental bone presents the most evident similarity to proper bone. There are found in it medullary tubes (canals of the pulp) and medullary fibres (fibres of the pulp), round which groups of concentric layers have been formed; from these the minute tubes radiate, which in the different layers are as it were pieced together, and in these layers concentric rows or rings of cells are again found, just as in bones." And again, when describing the teeth of the Pike, he says of the large tubes that in a few recent teeth "they contained a blood-red substance, and may hence be regarded as divisions of a cavity of the pulp." (NASMYTH 'On the Teeth,' p. 105.)

As Professor OWEN'S definitions and descriptions of vaso-dentine and osteo-dentine are generally accepted and followed, it is necessary to gather from his writings extracts which will show what precise meaning he attaches to the terms, and indeed little exception could be taken to his grouping of the varieties of dental tissue, were it not that his classification is not based upon, and indeed sometimes conflicts with, the evidence derived from a study of their development.

Vascular-dentine is described by Professor OWEN ('Odontography,' p. xvii.) thus: "The prolongation or persistence of cylindrical canals of the pulp cavity in the dentinal tissue, which is the essential character of vascular dentine, manifests itself under a variety of forms. In mammals and reptiles these canals, which I have termed 'medullary' from their close analogy with the so-called canals of bone, are straight and more or less parallel with each other; they bifurcate, though rarely, and when they anastomose, as in the Megatherium, it is by a loop at or near to the periphery of the vascular dentine. In the teeth of fishes, in which the distinction between the dentinal and osseous tissues is gradually effaced, the medullary canals of the vascular dentine, though in some instances straight and parallel and sparingly divided or united, yet are generally more or less bent, frequently and successively branched, and the subdivisions blended together in so many parts of the tooth as to form a rich reticulation. The calcigerous tubes sent off into the interspaces of the network partake of the irregular character of the canals from which they spring, and fill the meshes with a moss-like plexus.

* * * * * *

"If the first described modification of vascular dentine which forms the chief part of the teeth of the Sloth and Megatherium be regarded as a fourth dental tissue (*i.e.*, enamel, cement, dentine, and this), this second modification of vascular dentine from its close resemblance to bone might be reckoned as a fifth; in proportion, however, as it resembles bone, so, likewise, it approaches to the structure of cement."

At a subsequent page Professor OWEN further subdivides vascular dentine into three varieties. The first in which all the medullary canals are parallel, each having its own distinct system of dentinal tubes, as in *Pristis* or *Myliobates;* the second in which the anastomoses between the medullary tubes are more numerous, and the boundaries between the component denticles less distinct, as in *Cestracion;* and

the third in which the dentine is permeated by a network of medullary canals, of which the interspaces are occupied by the calcigerous tubes and cells. The canals ramify and anastomose abundantly, as in Lamna, and in the Percoid, Lucioid, and Gadoid families.

In his 'Anatomy of Vertebrates' (vol. i. p. 361), he says: "The simplest modification of dentine is that in which capillary tracts of the primitive vascular pulp remain uncalcified, and permanently carry red blood into the substance of the tissue.

"These so-called 'medullary' or 'vascular' canals present various dispositions in the dentine which they modify, and which is called 'vaso-dentine.'

* * * * * *

"A third kind of dentine is where the cellular basis is arranged in concentric layers around the vascular canals, and contains 'radiated cells,' like those of osseous tissue; it is called 'osteo-dentine.' The transition from dentine to vaso-dentine, and from this to osteo-dentine, is gradual, and the resemblance of osteo-dentine to true bone is very close."

Hertwig (Ueber Bau und Entwickelung der Placoidschuppen und der Zähne der Selachia. Jenaische Zeitschrift, 1874), in describing the dentine of Shark's teeth speaks of the frequent absence of a definite pulp-cavity, its place being taken by a canal system containing cells and blood-vessels. He notes the absence of a definite odontoblast layer upon the formative pulps of either teeth or scales (which are practically speaking the same in these respects), but says that the cells which do lie upon the surface, though not forming a very sharply defined layer, play the part of odontoblasts. He also compares their method of calcification to that of osteoblasts, and notes the occurrence of similar cells in the larger canals far within the formed dentine.

His description of the dentine met with in these scales and teeth, as well as of their development, would bring the tissue so formed within the restricted meaning which I have proposed in the following pages for the term osteo-dentine, a result at which I had myself arrived.

The foregoing extracts, few though they are, embody most of the facts of importance which I can find upon record; and what little mention is there made of the relation of vascular dentine to the formative pulp and of the contents of its larger tubes, appears not to have been grounded upon observation so much as upon *d priori* deductions.

As I shall endeavour to show, the study of their development must lead to the discrimination of at least three varieties of vascular dentine, but since the terms vaso-dentine and osteo-dentine are in common use, it will be far more convenient to retain them instead of introducing new terms, merely limiting and rendering exact their application, which is at present as vague as it well can be. For the third variety also a name already in use may be found which will describe its nature with sufficient accuracy.

The teeth of the common Hake throw so much light upon the question to be discussed that I will commence by a description of their minute structure. They are conical, slightly recurved, and very sharply pointed, being furnished with a sort of spear-point of enamel (see *a*, fig. 1, Plate 3), as are the teeth of all the Gadidæ which I have been able to procure.* They are arranged in a *double*† row round the margins of the mouth, the outer row being firmly anchylosed, and the inner row set upon an elastic hinge, which allows them to bend inwards towards the mouth, like the hinged teeth of the *Lophius piscatorius* (see page 41 of this paper); the teeth situate near to the front of the mouth of a Hake which weighed 11 lbs. (in poor condition) are $\frac{1}{2}$ of an inch in length. The teeth are hence rather conspicuous, and they are made more so in a freshly-caught fish by their bright red colour; the dentine is very transparent, and the pulp is richly vascular, so that the red blood is seen through the exterior of the tooth, in the tubes of the dentine of which it, as will be presently seen, actually circulates.

When viewed with a low magnifying power the axial pulp-chamber is usually seen to be of large size relatively to the whole tooth, and the dentine to be permeated through the greater part of its thickness by a system of canals which spring from the pulp cavity (see fig. 1).

These canals are of almost uniform diameter in the different parts of their course, measuring from $\frac{1}{8000}$ to $\frac{1}{3500}$ of an inch in diameter; they are arranged with great regularity, radiating outwards from the pulp cavity, and terminating by anastomosing with neighbouring tubes, forming squarish-ended loops towards the surface of the dentine. Owing to this flattening of the ends of the loops and to the tubes all stopping short at the same distance from the surface, an outer layer of dentine into which no such tubes penetrate is sharply marked off (*d* in fig. 1).

No fine dentinal tubes are given off from these canals, which do, however, here and there give off quite short prolongations of smaller calibre; these are not, either from their size or frequency of occurrence, of much importance.

But the point of greatest interest about the teeth of the Hake is the nature of the contents of these larger tubes. *Each tube contains a capillary blood-vessel*, and *nothing else;* the thin wall of the capillary being in actual contact with the hard dentine of the completed tooth, and no other soft tissue being interposed. In fact, the tubes in the dentine are just the size of the capillaries of the pulp, and red blood is circulating through the capillaries enclosed in the dentine when the tooth is in use, just as it might be circulating in the capillaries of the pulp prior to its calcification. Thus blood is brought close to the surface of the dentine, and this, with the abundance of the tubes, it is that gives to the tooth of the living or freshly-killed Hake its brilliantly red colour.

* Namely, the Cod (*Gadus morrhua*), Haddock (*G. æglefinus*), Whiting (*Merlangus vulgaris*), Coalfish (*M. carbonarius*), Pollack (*M. pollachius*), Hake (*Merluccius vulgaris*), and Ling (*Lota molva*).

† They are often, owing to a fact respecting their attachment to be presently described, supposed to form a single row only.

This is well seen in fig. 2, which is a section of dentine cut with a sharp knife from the tooth of a Hake within a couple of hours of its capture. From the edge of the dentine there hang out (at *cp*) torn capillary vessels, from the ends of several of which hundreds of blood corpuscles were slowly flowing out as I was making my drawing. The section was also sufficiently thin to allow of the blood corpuscles contained in the capillaries within the dentine to be distinguished through its substance, as is seen in the figure.

This dentine may therefore be most appropriately called VASO-DENTINE, and no better name could be found by which to designate it; but I confess myself unable to see what useful purpose can be served by the rich vascularity of the dentine; it would seem improbable that the dentine should need nutriment, for the teeth of the Hake, like those of most fish, are obviously frequently shed off and renewed, and there are five or six teeth in preparation for every one that is in place and at work. And this rich plexus of capillaries is the less intelligible as the intervening dentine is of unusually dense and impermeable structure, and, one would think, was as little in need of vascular supply as anything which remains in continuity with a living organism could well be.

In the clear external layers of dentine a very faint striation perpendicular to the surface can be made out, but I have entirely failed to make out the existence of any thing like tubes in it, whether by the use of powers as high as a $\frac{1}{11}$nd objective, or by the endeavour to get coloured fluids to penetrate them. I am pretty well satisfied that no tubes exist, but that the indistinct striation is simply a result of the manner in which the tissue was developed, as will be presently described.

In addition to the markings just alluded to, there is a faint striation of the whole dentine in line, roughly speaking, parallel with its surface. Like the striation of the peripheral dentine, these lines probably do not represent any tube system; but may be due to successive depositions of calcified material on the interior of that already formed, and mark lines of growth.

A tooth which has been decalcified shows sometimes a tendency to split up along these lines, but although I have used a variety of processes and examined very fine sections taken in many planes, I cannot make out the existence of actual tubes in the interspaces of the large capillary canals. But the vascular canals are so close together that there is comparatively little interstitial tissue, and the nature of the dentine matrix may be more advantageously studied in the teeth of other Gadidæ, such as the Cod, in which the vascular loops are not quite so close to one another, and in describing the teeth of that genus I shall recur to this matter.

The pulp of the tooth of a Hake is, like its dentine, remarkable for its vascularity; at first sight it appears to consist of nothing whatever besides blood-vessels and odontoblast cells, the latter being upon the surface. More minute examination reveals the existence of a very delicate connective tissue binding it all together, but the great bulk of it really does consist of blood-vessels.

If the pulp be withdrawn from a tooth, and slightly teased out, capillaries filled with blood and clothed upon their surfaces with odontoblast cells may be abundantly found; the odontoblast cells are apparently seated directly upon the capillary, no connective tissue nor other cells intervening (see fig. 7); by the calcification of these odontoblasts the capillary vessel would obviously become closely embraced by hard dentine.

And this is a strong argument in favour of what is known as the "conversion theory" of the development of dentine; supposing these odontoblasts to be calcified and themselves converted into dentine, there is no difficulty in seeing how the capillary comes to be enclosed in a tube of dentine having the same calibre as itself. But if the odontoblast cells "secrete" the dentine, as maintained by HERTZ and others, how is the process to be completed when there is no longer room for an entire odontoblast or the half of an odontoblast between the rigid wall of already formed dentine and the capillary? One can hardly conceive a secreting cell going on shedding out from its end its secretion when it has been reduced to, say one-tenth, of its length; and unless one is prepared to accept such a conception, this observation of the structure of a Hake's tooth-pulp becomes fatal to any "secretion" hypothesis of the formation of dentine.

There is not much difficulty in procuring sections which show the relations of the pulp and the dentine *in situ*, if the teeth and their contents be hardened and decalcified in chromic acid; I have found immersion in ½ per cent. solution for ten days to be effectual in decalcifying them sufficiently to enable sections to be cut with a razor, and much longer treatment with the acid decidedly injures the pulp tissues. A transverse section prepared in this way is represented in fig. 4; in cutting the sections the pulps have been to a slight extent dragged away from the dentine, but this is rather an advantage than not, as it renders the figures clearer than they would otherwise be.

In fig. 4 several capillaries (*cp*) are seen stretching across from the pulp and entering the substance of the dentine, each one fringed with its layer of odontoblast cells; in the axial portion of the pulp are seen the cut ends of the numerous blood-vessels which make up so large a part of its bulk. In fig. 9 the distribution of the odontoblast cells is also seen; they clothe the whole surface of the pulp, and where there is a capillary at the surface they clothe it, so that when they calcify the capillary becomes solidly embedded in dentine.

The capillary plexus does not extend quite to the surface of the original formative pulp, so that the outermost layers of the dentine are formed from the continuous sheathing of odontoblasts which invests the pulp, and hence contain none of the larger capillary canals. A portion of the thin decalcified dentine cap taken from a tooth-sac in which calcification had only just commenced is shown in fig. 6. It will be seen that the rods, so to speak, of dentine formed from the several odontoblast cells have not entirely coalesced, and show a tendency to separate from one another;

this explains the appearance of faint striation in the outer layer of dentine, in which nevertheless no tubes nor real interspaces exist.

Some isolated odontoblast cells are shown more highly magnified in fig. 5; the constrictions in their middles are due to the shrinkage caused by absolute alcohol, the end next to the dentine (*q*) being apparently too rigid to shrink, and the presence of the oval nucleus preventing shrinkage at the opposite extremity; examined in serum they are of uniform diameter.

The odontoblasts of the Hake measure about $\frac{1}{800}$th of an inch in length and $\frac{1}{6000}$th of an inch in diameter; they are, after calcification has once commenced, furnished with a variable number of fine processes at the end next to the dentine, which project for a little way into it; but they do not remain permanently uncalcified, like the dentinal fibres of Mammalia. The opposite end of the cell tapers off into a fine process, but I have never detected lateral processes connecting them with their neighbours. The nucleus is oval, very distinct in some of the cells, but sometimes indistinguishable; I have been unable to discover under what conditions this is the case. I have described the structure of the tooth of the Hake at some length, because I am not acquainted with any description of it in the pages of writers on odontology, nor with any other tooth which so clearly exemplifies the true nature of this kind of vaso-dentine. But before proceeding to remark upon the teeth of certain other Gadidæ, I will quote Retzius' description of the dentine of the Ling.

As quoted by Nasmyth ('On the Teeth, 1839,' p. 107,) Retzius thus described the dental tissues of the Ling:—"Along the wall of the cavity of the pulp, which ran longitudinally, and was in part tubiform, the main tubes opened with short trunks of from $\frac{1}{50}$ to $\frac{1}{70}$''' p.m. ($\frac{1}{850}$th of an inch, about) in thickness, which ran towards the apex and in an outward direction, and gave off branches on both sides, between which there were considerable intervals; these branches formed, with others of the contiguous tubes, large loop-shaped anastomoses, and their outer extremities entered also into closed anastomoses, *almost like the more minute blood-vessels in the villi of the abdominal canal.*"

"The more minute lateral branches of the tubes of the dental bone in the Ling were not easily discovered; they appeared to be less regular, and generally ran in a direction transverse to the tubes from which they rose, or parallel to the axis of the tooth."

From the passage which I have italicised, it will be obvious that Retzius suspected the true nature of the contents of the larger canals which permeate the tooth of the Ling, and Professor Owen's name of vaso-dentine would imply the same interpretation, but the latter's more detailed description does not confirm the supposition that he believed the tubes to be occupied by capillaries and capillaries alone.

Thus he writes of the dentine of the Gadidæ:—"Processes of the pulp are conveyed by medullary canals which diverge from all parts of the main central

cavity into the substance of the dentine; these are about $\frac{1}{800}$th of an inch in diameter at their origin, but they quickly divide, and their branches form anastomoses with those of the neighbouring tubes; the loops thus formed by the smaller terminal branches constitute a well-defined boundary between the coarse central and the fine external dentine.

"In this latter the calcigerous tubes, which are about $\frac{1}{18000}$th of an inch in diameter, proceed as usual, parallel to each other and parallel to the axis of the tooth at its apex, but transversely to that axis at its sides" ('Odontography,' p. 163).

The tooth of the Cod differs in some particulars from that of the Hake, so that it may be worth while for me to briefly describe its structure.

Cod (*G. morrhua*).—The teeth are not so slender as those of the Hake, and they are more solid, the pulp being smaller relatively to the size of the completed tooth. Just as has been described in the case of the Hake, the dentine of the Cod is permeated by a system of canals about $\frac{1}{3000}$ in diameter, which form loops and anastomoses with one another, just as do the capillaries of the pulp prior to the commencement of calcification around them. These tubes contain, in the fresh condition, capillary vessels in which blood circulates; in fact the only difference between the dentine of the Cod and that of the Hake lies in the arrangement of the capillary channels, which are less abundant in the dentine of the Cod, and form loops with rounded instead of with flattened ends, so that the boundary of that external layer of dentine which is not permeated by the tubes is less sharply pronounced. In a longitudinal section there is faint striation running in the long axis of the tooth or rather parallel with its surface; this is to be seen in all parts of the tooth, but the striation is most pronounced near to the base.

Under a high power this appears (in longitudinal sections) like parallel tubes, about $\frac{1}{30000}$th of an inch in diameter, but they do not start either from the pulp cavity or from the vascular canals, and there is an exactly similar appearance in the bone which supports the tooth (*c* in fig. 25).

No coloured solution can be induced to enter them, even by boiling the thinnest sections in it, or by placing the sections immersed in the fluid under the receiver of an air-pump and exhausting the air as completely as possible. Nothing can be seen of tubes in transverse sections, and their direction is parallel to the long axis of the tooth, so that, if these striæ are tubes, they are at right angles to the ordinary course of dentinal tubes, and at right angles to the long axes of the formative odontoblast cells.

But the most conclusive evidence as to their not being the representatives of the dentinal tubes of other creatures is derived from an examination of the teeth of some members of another family, viz., the Pleuronectidæ. In this family the teeth are composed of vaso-dentine of the same type as that possessed by the Gadidæ, with this difference, that at their apices the dentine is poor in vascular canals, but is permeated by an abundance of true dentinal tubes. Passing downwards from the enamel-tipped apices of the teeth the vascular canals become more and more abundant, and the dentinal

tubes become fewer and fewer, irregular in course, and finally one third of the way down altogether cease (see fig. 10*). But the lower portion of the dentine which is devoid of dentinal tubes presents the longitudinal striation, and is, in fact, precisely like the dentine of the Gadidæ. And at the point where the dentinal tubes are few in number (*t* in fig. 10*), the longitudinal striation is traversed by transverse dentinal tubes, thus proving by the co-existence of the two that they are due to different and independent causes.

I cannot therefore confirm the opinion of Retzius and Professor Owen, that the whole tooth substance of the Gadidæ is permeated by a minute tube system: on the contrary, I believe it to be quite solid.

But although it is solid the matrix of the dentine is not quite homogeneous; in transverse section very faint striæ radiate outwards from the pulp cavity, and the spaces between the striæ (the distinctness of which has been intentionally slightly exaggerated in fig. 7) are mapped into a finely reticulate pattern.

Under a higher magnifying power this pattern is found to present the appearance shown in fig. 3, and as this appearance is found alike in transverse, longitudinal, and oblique sections, it is probable that it is due to calcification first taking place in such manner as to form isolated globules (as indeed happens to a greater or less extent in all varieties of dentine), and to these globules failing to completely coalesce but becoming modified in form by mutual apposition.

That that is the true interpretation of the nature of the pattern is indicated by the occasional occurrence of globules which have not been thus distorted, but retain their spherical form, and also by the appearance of fine reticulation in the dentine of the teeth of allied fish, such as the Pleuronectidæ.

The pulp is less rich in blood-vessels and far more rich in connective tissue than that of the Hake; otherwise, it does not call for any special description. On its surface the odontoblast cells form a very distinct layer about $\frac{1}{1000}$ of an inch in thickness, and capillary vessels may be seen running out from the pulp through the odontoblast layer into the dentine (see fig. 9). But I have never seen capillaries clothed with odontoblasts like that of the Hake represented in fig. 7, though this may be due to my never having examined a Cod-fish so freshly caught as was the Hake from which fig. 7 and fig. 2 were drawn.

The dentine in the Haddock, Whiting, Coalfish (*Gadus carbonarius*), Pollack, and Ling, does not differ in essential particulars from that of the Cod. The frequency, size, and the form of the capillary loops vary, so that anyone well familiarised with their respective appearances might probably succeed in identifying them, but the differences are in minor points, and the structure of the matrix is similar in all.

In all of them we have the same essential features, the penetration of actual hard dentine by capillary vessels, and the absence of true dentinal tubes.

But although I have not found the dentinal tubes in any of the Gadidæ which I have examined, and although their absence is the rule in this modification of dentine, no

mention of this peculiarity can be made in a definition of vaso-dentine, as in the teeth of Pleuronectidæ, which are obviously of the same type of structure, the dentinal tubes exist near to the tip of the tooth, as seen in fig. 10.*

And although, as a rule, the outermost portion of the dentine is dense, and is not permeated by the vascular canals, this dense external layer is not found in all such teeth. For instance the teeth of *Ostracion* (fig. 10) are composed of this vaso-dentine, but the vessels extend right up to the surface of the dentine, and the thick and strongly coloured enamel which clothes their teeth takes the place of the dense dentine of the surface. The transition between vaso-dentine of the type just described, and the ordinary hard dentine of Mammalia teeth is tolerably gradual. Thus in the Pleuronectidæ (fig. 10*) we have a tooth the apex of which is composed of hard unvascular dentine with true dentinal tubes, whilst its lower two-thirds have abundant vascular capillary canals, but no dentinal tube. In *Serrasalmo* (fig. 11 and 11*) we have a tooth the upper half of which consists of ordinary (at least for the present purpose ordinary) fine tubed dentine, and in it the dentinal tubes permeate the dentine of the base as well as that of the upper portion of the tooth.

But near to the base of the tooth there are a few capillary canals; by the suppression of these we should get ordinary unvascular dentine. The interpolation of capillary tracts in dentine is not unknown amongst Mammalia; thus it is found in the Megatherium, in the Tapir, and in the Manatee, though whether red blood really does circulate through them in the completed tooth is not definitely ascertained. From this variety of dentine, most appropriately called Vaso-dentine, the relationship of which to unvascular dentine has been shown, we pass to the consideration of a very distinct variety, which although hitherto universally known as vaso-dentine, has in reality very little relationship to that tissue.

Of the teeth of the Pike, Retzius (as quoted by Nasmyth, 'On the Teeth,' 1839, p. 104) says, "The dental bone itself in the Pike is properly divided into an internal kernel provided with large tubes, and into an external thinner part, which latter forms the covering of the first, and contains minute and parallel tubes. The large main tubes which occupy the internal more imperfect part of the dental bone, are in their widest part about $\frac{1}{85}$ p.m. ($\frac{1}{300}$ of an inch) in diameter. They run almost parallel with each other, and with the axis of the tooth, and form with each other numerous larger and smaller anastomoses.

"Near the base of the firmly fixed teeth, the larger transverse anastomoses are so near to each other that the interstices are scarcely as wide as the diameter of the large tubes. In some few recent teeth these tubes contained here and there a blood-red substance, and may hence be regarded as divisions of a cavity of the pulp.

"Here, too, those (larger tubes) which are near to the apex run almost parallel with the axis of the tooth; but those which are nearest the root transversely to it, and so on. They divide at their commencement into bundles of larger and smaller branches, which enter into numerous reticular anastomoses with each other, but which

most externally give off very beautiful, close, parallel, generally straight tubes of about from $\frac{1}{1500}$ to $\frac{1}{3000}$ p.m. ($\frac{1}{13000}$) of an inch in breadth;" amongst the latter RETZIUS could discover neither branches, anastomoses, nor cells.

"This most external stratum of dental bone gives to the transverse sections of the tooth of a Pike a peculiar and pretty appearance, and resembles, slightly magnified, a layer of enamel.

"This minutely tubular external portion of the dental substance is of the purest white, and is also much harder and more compact than the interior of the dental bone. To judge by the hardness of the surface in dried teeth, RETZIUS would have concluded that it was invested with an extremely thin layer of enamel; but he could not detect any with the microscope, although accurate authors have asserted that it is present on teeth of the Shark."

Professor OWEN adds nothing to RETZIUS' description—there is, in fact, little to be added, as it is both accurate and comprehensive. But as I wish to emphasize the points of difference between this and the vaso-dentine just described, I will add a few words to it.

Dentine of the Pike.—Both in its structure and in its development this differs markedly from the form of vaso-dentine first described; in fact it is a misnomer to call it vaso-dentine at all. The dentine is divisible for descriptive purposes into two portions: an outer which is permeated by numerous fine tubes perpendicular to the surface, like the tubes of ordinary unvascular dentine, and an inner which is of much coarser structure and is permeated by large irregular spaces having a general longitudinal direction (see fig. 13).

The tubes of the outer layer are parallel and end apparently short of the surfaces; they are about $\frac{1}{10000}$ in diameter.

They spring, through the intervention of short branches of intermediate size, from the larger spaces of the coarse core of the tooth (see fig. 14). These latter form longitudinal canals of varying diameter and irregular form; they give off from their sides and ends branches which abruptly subdivide and become small; at the point where these merge into the fine dentinal tubes of the exterior they lose their tubular form and are dilated into irregular spaces of small size, like small bone lacunæ or the interglobular spaces of the granular layer of human dentine. From these spaces originate the dentinal tubes (see fig. 14).

There is thus a strongly marked difference between the dentine of the Pike and that of the Gadidæ, even when the structure of the hard tissues of the tooth alone is considered, but the distinction between the two varieties becomes yet more marked when the relation of the soft parts to the dentine is also taken into account.

For the larger longitudinal canals of the Pike's tooth do not, except as a matter of accident, contain capillary blood-vessels; that is to say, the dentine as it is formed is not deposited round capillaries, so as to enclose them within itself, and hence very few of the channels do contain capillaries; when they do, the capillary only forms a

part and not the whole contents of the tube. In the fresh condition the channels of the dentine contain a firm cellular tissue, not unlike that which forms the bulk of most tooth pulps, but it is exceptional for it to be rich in vessels.

The nature of the contents of the channels will be best understood by following out their development.

Of the development of the Pike's tooth Professor Owen ('Odontography,' p. 133) tells us "that the formation of a tooth is an act of conversion of the substance, and not of cells upon a formative surface of the pulp, is clearly illustrated in the Pike. The cone-shaped cap which the half-developed tooth forms upon the remaining matrix can only be removed by overcoming a certain resistance, and this resistance is seen to be due to the processes of the pulp which extend into the medullary canals of the tooth; the broken ends of these processes give an irregular surface to the exposed pulp, and their continuation into the tooth may be seen by sawing the latter across. This connection between the substance of the tooth and of the pulp is still better seen in a finely injected specimen; the mechanical relation between the tooth and the pulp is then seen to be of precisely the same kind as those between an ordinary osseous nucleus and the cartilaginous matrix in which it is developed; it is in the course or direction of development that the chief difference exists; in the tooth it is centripetal, in the bony epiphysis centrifugal, but the mode of development is the same."

An early dentinal pulp from the jaws of a Pike does not present any special peculiarity; it is a conical mass of richly cellular tissue, the surface of which is covered as by an epithelium, with a layer of larger elongated cells, which do not form so distinct and sharply defined a layer as the odontoblasts of most dentinal pulps. By the calcification of these the exterior layer of fine tubed dentine is formed in the ordinary way, and presents no peculiarities worth description. But no sooner is the thickness of this outer layer (*f* in figs. 13 and 14) completed, than the nature of the process of calcification becomes profoundly changed; the remainder of the dentine is not formed by the calcification of the more or less defined layer of cells corresponding to the "membrana eboris," but by an extension of calcification through the mass of the pulp in a manner to be presently described. The surface of the pulp in immediate contact with the dentine already formed is no longer clothed with a continuous layer of odontoblasts, but the cells which are near to the surface become aggregated into masses, between which there appears an almost structureless transparent tissue, which then forms trabeculæ shooting from the dentine into the substance of the pulp between the cellular aggregations. Calcification follows very close on the heels of the formation of this tissue, and a longitudinal section of a pulp at this stage (see fig. 15) shows the extent to which the whole mass of the pulp becomes penetrated by these calcifying processes. Their course as they run down into the pulp is not at all determined by the position of the capillaries, in which the pulp is not rich; on the contrary, they extend in almost straight lines from the dentine already formed down into the pulp, and subsequently become

connected with one another by cross branches. The canals of the completed tooth are the spaces left out by and included between these tracts of calcification; the contents of the canals are the masses of pulp so enclosed.

If the calcifying dentine of one of the Gadidæ be compared with this of the Pike, it will be seen that the internal surface of the former to which additions are being made is smooth and of even outline (see fig. 4 and fig. 9), whereas the internal surface of the latter is extended out into a large number of greatly elongated processes. This is well seen in the transverse section represented in fig. 16*. In fig. 16 the ends of one or two of the processes to which additions are being made are represented. The growing surfaces are found to be covered with a layer of nearly spherical cells, like the osteoblasts by which bone is built up; but there are no elongated cells, such as are ordinarily called odontoblasts, to be found. In fact, viewing the tooth of the Pike from the point of the minute development of its constituent parts, it might not inaptly be described as consisting of a core of porous bone coated over with a thin skin of dentine, and, had not the name osteo-dentine been somewhat loosely applied to other tissues than this, no more fitting term by which to designate it could have been found. The teeth of those PLAGIOSTOMI which have been examined by HERTWIG and by myself are developed in a manner precisely similar, as might be expected from their structure.

Thus far I have sought to distinguish from amongst the tissues hitherto indiscriminately classed as vaso-dentine two strongly marked varieties.

(1.) A dentine formed wholly by calcification of a layer of special odontoblast cells, and permeated by a system of canals formed around and enclosing capillary blood-vessels.

To this variety I would apply, and to it strictly limit, the application of the term VASO-DENTINE.

(2.) A dentine formed at its surface only by a cellular layer, its interior being formed by the extension of calcifying trabeculæ through the substance of the pulp. It also is permeated by larger channels, but these bear no relation to capillary blood-vessels.

To this variety I would limit the application of the term OSTEO-DENTINE.

There is at least one other way in which the structure of dentine may become complicated, and in which it may come to contain a system of channels larger than dentinal tubes. The formative pulps of the two varieties of dentine to which I limit the terms vaso-dentine and osteo-dentine are simple cones, but the surfaces of the pulps themselves may be complicated by various folds and inflections, so that by their calcification a complicated looking tissue results.

As an example of this I have figured the transverse section of a tooth of *Lepidosteus osseus*, which I was so fortunate as to procure in chromic acid solution (fig. 12).

In this the complication of the tissues is due to complication in form of the formative pulps; the whole of the dentine is formed by the calcification of odontoblasts, thus

contrasting with that of the Pike, which is formed from a *simple* pulp by an irregular calcification running through its substance, and which is only in very small part formed from odontoblast cells.

Dentine which has been formed from a convoluted pulp may attain to great complexity of structure, as happens in the *Labyrinthodon*, or the sub-division of the formative pulp may result in the production of a tooth which might be regarded as an aggregation of denticles, as happens in the *Myliobates*.

But although in this way considerable variety is arrived at, and the tissues bear a more or less close resemblance to osteo-dentine, yet there is one character which will generally serve to distinguish these from it.

Each of the larger canals in the completed tissue forms an axis from which dentinal tubes radiate with some degree of regularity, these dentinal tubes having resulted from the calcification of the layer of odontoblasts with which each subdivison of the formative pulp was clothed; whereas, in osteo-dentine, like that of the Pike, no such distinct and regular systems of dentinal tubes radiate from the larger canals.

The true character of dentine derived from a convoluted pulp is not badly expressed by the term PLICI-DENTINE, already applied by Professor OWEN to some examples of this structure, and it would embrace dentine of every degree of complexity, from that of such teeth as those of the *Lepidosteus*, which are simple in their apices and not very greatly complicated at their bases, to such as those of the *Labyrinthodon*.

An exceedingly instructive modification of dentine structure is to be found in the teeth of the Sparidæ, of which I have examined *Sargus ovis*, *Chrysophrys* ——(?), and *Pagellus*.

The manner in which their teeth are supported is very curious; if a longitudinal section of a front tooth and the bone beneath it of *Sargus* or of *Chrysophrys* be very carefully made (the tooth is easily broken off at the level of the bone, and the section can only be made by a skilled hand with a lapidary's wheel), it will appear to the naked eye as though the tooth were furnished with a long root, half as long again as its crown, implanted in a socket of bone to which it is anchylosed; whilst at its upper part this "root," if such it can be called, is sharply defined, at its lower end or apex it merges into the surrounding and subjacent bone.

It has already been incidentally mentioned that the tooth readily breaks off at the level of the surface of bone, easily parting from its implanted portion; if a section such as that described be rubbed down and examined microscopically, it will be found that there is a rather abrupt change of structure at the point alluded to. The outstanding portion or crown of the tooth (*d* in fig. 23 and 24, Plate 3) is composed of hard fine-tubed dentine coated with enamel; the implanted portion (*d'* in same figures) of vascular dentine. The pulp cavities of the two segments of the tooth are continuous and of the same diameter, and so are the walls of dentine (in fig. 17, the pulp cavity of the implanted portion is not shown, because the section is oblique, and does not pass truly along the long axis of the tooth). In tracing the development

of the teeth, I find (in the case of *Sargus*, the only one which I have been able to procure fresh, or preserved from the first in chromic acid) that the exserted and implanted portions of the teeth are alike developed from the same dentinal pulp (see *k* in fig. 23), and, what is somewhat remarkable, I cannot detect any difference in structure between that upper portion of pulp which is engaged in forming hard dentine, and that lower portion which is building up vaso-dentine, save only that this latter part is more richly vascular. Why the pulp should at a particular point cease to form "hard" dentine, I cannot see; possibly had I been successful in making an injection, which I attempted, but failed in effecting, the distribution of the vessels might have explained it.

In the implanted portion, near to the point where the change takes place (see figs. 19 and 20), the pulp is furnished with odontoblasts, and the dentine formed is the vaso-dentine with a few true dentinal tubes, the large channels being the spaces left for and occupied by capillaries. Lower down no dentinal tubes occur, and the dentine presents the appearance represented in fig. 21, whilst in a fully completed tooth we find near to the end of the root the shell of vaso-dentine (*d'* in fig. 18) becoming thinner and thinner, whilst instead of its surrounding a central pulp chamber, this latter is blocked up by a coarsely reticulated calcified tissue (see also base of the left hand tooth in fig. 23). It is hard to say where the tooth ends, for the vaso-dentine thins out to nothing, and the coarse bone of the axial portion merges into that which surrounds and underlies the tooth, and serves to secure it by anchylosis to the walls of its socket (*c* in fig. 23 and 19). In the development of these teeth we have therefore a single dentinal pulp which at its apical part forms true or hard dentine; at a certain point it changes somewhat abruptly, and forms vaso-dentine, and then by more insensible gradations its axial parts, and finally its whole base, change their manner of calcification, and become converted into an osteo-dentine which blends insensibly with that coarse bone which is being formed outside the limits of the tooth pulp. No other tooth with the development of which I am acquainted shows with the same clearness as the tooth of *Sargus*, the relation of these several tissues to one another and to bone.

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It appears to me exceedingly undesirable to multiply names, so in the place of doing so, I would suggest merely rendering more precise and more limited the meaning attached to the terms VASO-DENTINE, OSTEO-DENTINE, and PLICI-DENTINE, to the latter of which, however, a more extended application than it has hitherto had must be given.

To summarise the result of the foregoing observations, we should distinguish four varieties of dentine, to be thus described:—

I. HARD UNVASCULAR DENTINE; a tissue wholly developed from the odontoblast layer of the dentinal pulp, and permeated by a system of dentinal tubes radiating from a central pulp chamber. Example; Human Tooth. This passes through gradational forms, such as that met with in the Serrasalmo (fig. 11*) and the Flounder (fig. 10*), into typical

II. VASO-DENTINE; a tissue without true dentinal tubes, although it is wholly

formed from the odontoblast layer of a simple pulp. It is abundantly permeated by tubes of larger calibre formed by the enclosure of, and containing, capillary blood-vessels. Example: Tooth of Hake.

Hard unvascular dentine derived from the calcification of a pulp of simple form, passes through gradational forms in which the bone of the tooth is fluted as in *Lepidosteus* (fig. 12) into

III. PLICI-DENTINE; a tissue with true dentinal tubes, which is derived from the calcification of a pulp, the odontoblast-carrying surface of which has been rendered complicated by infoldings of its surface. Example: Tooth of *Labyrinthodon*.

And lastly, we have typical

IV. OSTEO-DENTINE; a tissue devoid of true dentinal tubes (save in the form of a layer of hard dentine upon its surface) and derived from a calcification shooting through the whole substance of the formative pulp, so that it is not derived from a specialized odontoblast layer at all. The larger tubes do not contain capillaries, and its only complete distinction from bone lies in the fact of its development in a dentinal pulp, but not in the manner of that development. It is so closely akin to bone that the tooth of a Pike might be not inaptly described as a conical core of bone, furnished with a thin skin of hard dentine.

In the foregoing definition of osteo-dentine it may be noticed that no mention is made of the two characters by which Professor OWEN sought to distinguish that tissue, viz. the arrangement of the matrix in concentric rings around the vascular canals, and the presence of lacunæ similar to those of bone. These characters have been intentionally omitted for several reasons; the one, that there are many teeth the dentine of which I would, both from its development and its structure when perfected, class as osteo-dentine, in which neither of these characters is to be found, as, for example, the teeth of the Pike; another, that a concentric arrangement of the matrix around the canals is to be met with in vaso-dentine sometimes, and that lacunæ, or at all events spaces very similar in character, occur in dentine that no one would class as osteo-dentine; whilst lacunæ are absent both from bones and teeth in many fish whose teeth must, if my classification by developmental characters be adopted, be considered as consisting of osteo-dentine.

But although these are adequate grounds for leaving them out of the definition, it may save misapprehension to add that a laminated arrangement of matrix, and spaces similar to bone lacunæ, are, as might be expected, more commonly met with in the osteo-dentine than in any of the other forms of dentine.

When I commenced the examination of the teeth of Gadidæ, my object was not so much to investigate the nature of vaso-dentine, as to endeavour to ascertain how far minute structure was constant within the limits of a well-defined group. Unfortunately I have not as yet obtained materials sufficient to enable me to carry out my original purpose, to which I hope at a future time to recur, but I may here briefly indicate one or two of the facts which I have ascertained which bear on this question.

So far as I have been able to ascertain by an examination of the teeth of such Gadidæ as I could procure, true vaso-dentine, tipped with a spear-point of enamel, constitutes the teeth of all of the family. In the Pleuronectidæ we find the same thing, viz. true vaso-dentine tipped with a point of enamel, but the teeth (fig. 10*) at their apices hardly differ from unvascular dentine, while their bases are typical vaso-dentine. This structure, the true dentinal tubes being in greater or less abundance at the apex, exists in the teeth of the Pleuronectidæ commonly used as food. On the whole we might conclude that, so far as minute structure goes, the teeth within the limits of these two families are of one type. A similar agreement in minute structure is met with in *Sargus*, *Dentex*, *Pagellus*, and *Chrysophrys*. But one type of minute structure does not run throughout larger groups, such as Orders, thus for example, amongst PHYSOSTOMI the Eels have hard unvascular dentine: some Siluroids have true vaso-dentine; *Serrasalmo* has hard dentine, at its base merging into vaso-dentine (fig. 11*), and the Pike has osteo-dentine.

And great divergence in minute structure may be found within an Order which comprises far fewer genera than the PHYSOSTOMI.

Thus amongst PLECTOGNATHI, *Ostracion* (fig. 10*) has a tooth composed of vaso-dentine quite devoid of dentinal tubes, while *Balistes* has teeth composed of hard unvascular dentine; the teeth of *Gymnodonts* also are built up of unvascular dentine.

The subject is, however, too large a one for discussion in this paper, and the exceeding small number of fishes' teeth examined as compared with the vast number of genera and species comprised in the class, may well make a writer diffident in expressing any opinion as to the relation between minute structure of the teeth and general affinity.

Note on some Peculiarities in the Attachment of Teeth in the Gadidæ.

In the course of investigating the development of vaso-dentine in the teeth of the Hake, I became acquainted with some facts as to their attachment, which are in themselves so interesting that, although not quite relevant to the subject matter of the rest of my paper, I venture to append a short note describing them. That the predatory angler (*Lophius piscatorius*) was furnished with large teeth set upon an elastic hinge, so that they may be bent inwards towards the gullet, and when relieved from pressure at once spring up again, has long been known.

But I had not met with any mention of the teeth of the Hake, or indeed of any other fish, except Anableps and Pœcilia, being similarly attached to the bone which carries them.

Round the margins of the mouth, both in the upper and lower jaws, the teeth, which are sharply pointed and slightly recurved, are arranged in a *double* row. The outer row are strongly anchylosed to the bone; the inner row are attached by an

elastic hinge upon the inner sides of their bases, and are free on the outer side. They admit therefore of being bent inwards into the mouth, but they cannot be displaced outwards, and so soon as pressure is removed from them, they spring back into the upright position.

In the *Lophius* the outer row of (anchylosed) teeth in the lower jaw are insignificant in size as compared with the large hinged teeth, but in the Hake the disparity is not so great. The inner row in the latter fish are however much longer than the outer row and stand higher, and it is easy to see the benefit which a fish of its voracious habits, feeding amidst shoals of herrings, would derive from the mobility and elasticity of its longer teeth. In the dashes which it makes at its prey, if the latter were struck by fixed immovable teeth, either the herring would be thrown out of the way or the teeth broken; but with the elastic hinge with which they are furnished they would give way, the herring enter the mouth of the Hake, and the teeth resume their upright position.

However, not only are they movable, but they are in several ways modified so as to adapt them to this unusual condition. In fig. 26, Plate 4, one of these teeth is shown in a section transverse to the jaw; at the inner side its base is prolonged far below the outer side, and terminates in a thin edge, the elastic ligament being attached to this edge and to the outer surface of the tooth for some distance up its side, embracing rather less than half the periphery of the tooth.

The ligament is composed chiefly of waved fibres of elastic tissue, and returns the tooth to its upright position instantly when the pressure by which it was bent down is taken off. It is attached to a rugged surface of bone below, its surface of attachment upon the bone being much larger than that upon the tooth, so that it is somewhat fan-shaped, and it is perforated to give passage to the nutrient vessels of the pulp.

The tooth, as will be evident from an inspection of fig. 26, is sufficiently firm under a vertical pressure to make it serviceable as a piercing instrument, whilst it at once yields to an inward pressure.

The opposite or outer side of the base of the tooth is quite free, and in no way bound down to the bone beneath it, and instead of terminating in a thin edge, it is much thickened (see *d'* in fig. 26), especially on its internal aspect, so that it encroaches upon the pulp cavity of the tooth.

This thickened strengthened portion of the base of the tooth is received upon a sort of buttress of bone, which is built up to receive it, and the tooth abuts directly upon the bone, nothing in the way of a cushion being interposed. An inspection of the figure (fig. 26) will show at a glance that it would be impossible, without tearing or greatly stretching the ligaments, to bend the tooth outwards, whilst there is nothing beyond the elasticity of the ligament to prevent its bending inwards towards the mouth.

I had always wondered what became of the pulps of the movable teeth of the *Lophius* when its teeth were bent down, and had imagined it to be probable that the

vascular formative pulps had withered or undergone some form of degeneration prior to the teeth coming into use. But in the Hake, at all events, such is not the case; these movable teeth, capable of being, without injury, bent down to an angle of 60° with their normal position, are furnished with richly vascular pulps to the last.

The blood-vessels (*v*) enter the pulp through a perforation in the ligament (see fig. 27) at a point which undergoes little or no change of position when the tooth is moved, and the pulps have no connection with the parts subjacent, except in the immediate neighbourhood of the ligaments; and no blood-vessels enter it from below, as is usually the case in other tooth pulps.

When the tooth is bent down the pulp is therefore carried with it, and is lifted up from the bone beneath it, but no strain is put upon any part of it.

From the foregoing description it will be seen that the hinged teeth of the Hake have attained to an high degree of specialisation, and have in this matter of attachment attained to a close similarity with the teeth of *Lophius*, to which in structure they do not bear the smallest resemblance. Moreover the *Lophius* is an acanthopterous fish and the Hake one of the Gadidæ (Physostomi), so that they are sufficiently remote from one another. And as it was remarkable that one member of the family of Gadidæ should alone possess a structure believed to be very uncommon, I sought in other members of the family for any similar arrangement, and though I did not find it, I found what is of more interest, namely, what may be regarded as transitional steps towards its attainment.

Professor Owen ('Odontography,' p. 162) says, "All the teeth are less firmly attached to the bones in the Gadoids than in other osseous fish with laniariform teeth. In the Cod-fish the gelatinous conical pulp after having formed the body of the tooth, is continued in an uncalcified state, but condensed into ligamentous firmness, from the base of the tooth to the alveolar margin of the jaw; ossification then proceeds from the jaw along the ligaments towards the base of the tooth, which, however, rarely becomes anchylosed to the ossified ligaments. The teeth therefore of the Cod are generally detached in macerating the head, and the broad alveolar margin of the dentigerous bones is then covered by the ossified dental ligaments in the form of truncated cylinders of various sizes, the largest being the most external in the intermaxillary and the reverse in the premandibular bones."

It is thus well known that the teeth of the common Cod are not firmly anchylosed to the bone, so that they are often lost when the skull is macerated, being held in place by ligamentous fibres only. But it is not generally known, nor had I myself any suspicion until after examining the teeth of the Hake, that they (the teeth of the Cod) are normally possessed of a slight degree of mobility, and that they have sufficient resiliency to at once resume the upright position. Like the teeth of the Hake, they can be bent inwards towards the mouth, though only a very little way, and they cannot be bent outwards at all.

This is effected by the arrangement of bony support and ligament shown in fig. 25;

the inner side of the tooth extends to a lower level than the outer side, and is firmly bound down by dense ligamentous fibres (2 in fig. 25) to the bone beneath it.

On the opposite side, however, it is of different form; the dentine terminates in a sort of shoulder (2′ in fig. 25), which abuts upon a surface of bone shaped so as to fit it; to this it is bound down by a band of ligamentous fibres, but in such a manner as to allow of a certain small degree of motion, the extent of which will readily be appreciated by an inspection of fig. 25.

Thus in the Cod the outer side of the tooth, which was altogether free in the Hake, is so attached as to allow of slight mobility only. In other members of the family, *e.g.* the Haddock and the Coalfish (*Gadus carbonarius*), the base of the tooth is furnished with a similar sort of shoulder round its whole circumference, and by this it is fitted upon and into a short supporting cylinder of bone (see fig. 24).

This arrangement of course allows of practically no mobility whatever, and the Haddock, the Cod, and the Hake thus present three very instructive steps in the production of a highly specialised organ. The degree to which the little shoulder of dentine is fitted within the osseous cylinder beneath it varies much in different genera and species, but an attachment of this kind, completed by a few slight ligamentous fibres binding the parts together, may be taken to be the rule in Gadidæ and Pleuronectidæ.*

Description of Figures.

a. Enamel.
b. Vascular dentine.
c. Bone of jaw.
c′. "Bone of attachment."
c″. Specialised buttress of bone of attachment.
d. Hard dentine.
d′. Modified vascular dentine.
e. Formative cells of enamel-organ.
f. Finely tubular dentine in osteo-dentine tooth.
g. Large canals of osteo-dentine.
h. Calcifying trabeculæ—osteo-dentine.
i. Osteoblast cells.
k. Cellular tissue external to developing tooth (fig. 23 only).

* Since the foregoing paper has been in the hands of the Royal Society, I have found that the teeth in certain parts of the mouth of the common Pike are hinged; a description of the mechanism by which they are attached, which is very remarkable, will be found in the 'Quarterly Journal of Microscopical Science,' January, 1878.

l. Elastic ligament which attaches the Hake's and Cod's teeth.
o. Odontoblasts.
p. Formative dental pulp.
p'. Empty pulp chamber.
cp. Capillary blood vessels.
v. Artery entering pulp.

The lettering is the same in all the figures.

PLATE 3.

Fig. 1. Anchylosed tooth, consisting of vaso-dentine tipped with enamel. Longitudinal section. *Merlucius vulgaris* (Hake).

Fig. 2. Fragment of fresh Vaso-dentine from a Hake just caught, × 100. Capillary blood-vessels hang out from the edge of the dentine, and blood corpuscles are pouring out in abundance from one of the vessels.

Fig 3. Portion of dentine of Hake between the vascular canals, × 600. Longitudinal section. The matrix is not homogeneous, but looks as though made up of coalesced globules rendered somewhat angular by mutual apposition.

Fig. 4. Sections of dentine and surface of the pulp, the latter slightly dragged away from the former, × 100. Hake.

Fig. 5. Three isolated odontoblast cells, × 500. Hake.

Fig. 6. Surface of pulp, with thin layer of newly formed dentine, which tends to split up into rods, each one corresponding with an odontoblast cell, × 70. Hake.

Fig. 7. A capillary vessel with adherent odontoblast, × 100. Hake, taken from surface of pulp.

Fig. 8. Young tooth-sac, × 50. Hake. The largest enamel cells correspond in position to the future enamel cap.

Fig. 9. Section of base of tooth and of the pulp. Cod (*Gadus morrhua*).

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PLATE 4.

Fig. 10. Tooth consisting of vaso-dentine, the place of the ordinary external layer of hard dentine being supplied by a layer of thick enamel, × 50. *Ostracion.*

Fig. 10.* Tooth of vaso-dentine with an apex of hard dentine, × 40. Flounder (*Pleuronectes flesus*).

Fig. 10.** Tooth of hard dentine with base of vaso-dentine. *Serrasalmo.*

Fig. 11. Fine tubed dentine, with capillary canals interspersed in it, × 90. *Serrasalmos.*

Fig. 12. Transverse section of hardened and decalcified tooth and tooth-pulp, near to the base of the tooth, × 60. *Lepidosteus oxyrrhinus.* The radiating processes of pulp, each coated with odontoblasts, surround a central coarse meshed connective tissue framework (*p*).

Fig. 13. Tooth consisting of osteo-dentine, × 35. Common Pike, *Esox lucius.* A thin layer of fine tubed dentine (*d*) surrounds a central core of large channeled bony tissue.

Fig. 14. One of the larger canals of a Pike's tooth near to the surface, showing their connexion with the fine tubed layer (*f*) external to them, × 120.

Fig. 15. Section of developing tooth and dentine pulp of a Pike, × 30. From the first formed layer of hard dentine (*d*), run down trabeculæ (*h*) of rapidly calcifying tissue, which permeate the whole thickness of the pulp. No odontoblasts exist during this process.

Fig. 16. Trabeculæ from same specimen, × 200. Cells like osteoblasts (*i*) clothe their surfaces.

Fig. 16* and 16**. Transverse sections, somewhat diagrammatic, of a developing tooth of a Pike 16*) and of a Hake (16**). These show the even contour of the pulp forming vaso-dentine and the irregular contour of that forming osteo-dentine.

Fig. 17. Base of extruded (*d*) and upper part of implanted portion (*d'*) of tooth. Longitudinal section, × 50. *Chrysophrys.* The section not being true to the long axis of the tooth, the implanted portion appears solid, which it is not, having a central pulp cavity continuous with that of the upper part. At the junction of what might be termed crown and root the structure abruptly changes, fine tubed dentine above giving place to a tissue permeated by large channels (*d'*).

Fig. 18. Base of implanted portion of tooth, transverse section, × 30. *Chrysophrys.* The vascular dentine of the exterior is in the interior replaced by a very coarsely reticulated calcified mass (*d''*).

PLATE 5.

Figs. 19 and 20. Transverse section of teeth of *Chrysophrys* just at the junction of the implanted portion with that above the gum. The transition from the one type of structure to the other is abrupt.

Fig. 21. Portions of the vascular dentine more highly magnified. *Chrysophrys,* × 200.

Fig. 22. Dentine close to the point of transition, from fine tubed to vascular dentine. *Chrysophrys,* × 70.

Fig. 23. Developing teeth of *Sargus ovis.* On the left is a tooth just moving into place, on the right is a younger one.

Fig. 24. Tooth of a Haddock (*Gadus æglefinus*) with its supporting bone, showing its manner of attachment.

Fig. 25. Tooth of Cod (*Gadus morrhua*), a tooth of vaso-dentine attached to the supporting bone by ligaments (*l* and *l'*), which admit of slight mobility in one direction.

Fig. 26. Section of a hinged tooth of a Hake, with its pulp and supporting bone. It is attached to the bone on the left side by a ligament (*l*); on the right side its base is quite free, and thickened where, in its motions, it impinges upon the buttress of bone (*c''*) built up to receive it.

Fig. 27. Section of a hinged tooth of a Hake, showing the entrance of its vessels through a perforation in the ligament, an arrangement by which stretching of the vessels is avoided when the tooth is bent down.

IV. *On the Normal Paraffins.*—Part II.

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In my first paper on this subject I have shown that by the action of chlorine on a normal paraffin a primary chloride and a secondary one of the general formula

$$\left.\begin{matrix} C_n H_{2n+1} \\ CH_3 \end{matrix}\right\} CHCl$$

are formed simultaneously.*

I subsequently pointed out that other secondary chlorides, which are indicated by theory, are also probably produced at the same time.† I am still engaged with an investigation of this subject. It appeared of interest also to examine the action of bromine on the paraffins. The present paper contains the first results of this research.

Cahours and Pelouze state in their well-known paper on Caproyl Hydride (Hexane) that, while chlorine converts it into caproyl (hexyl) chloride $C_6 H_{13} Cl$, bromine at once replaces two atoms of hydrogen, the dibromide $C_6 H_{12} Br_2$ being formed; if, therefore, an equal number of molecules of the two bodies act on each other, one half of the hydrocarbon is not attacked.‡

Soon after I examined the action of bromine on heptane, and found that when a mixture of the two substances is exposed to the sunlight, or heated in sealed tubes to 100°, hydrobromic acid is slowly evolved, but the substitution products thus formed began to decompose at 110°, hydrobromic acid being given off and carbonaceous matter left behind.§

The satisfactory results which I obtained by acting with chlorine on the vapour of the boiling hydrocarbons, which were thus almost entirely converted into monochlorides, induced me to try the action of bromine under similar conditions.

The apparatus which I employed was very similar to that described in my former paper. It consisted of a flask holding about one litre, which was closed with a doubly-perforated cork, provided with a bulb-funnel, with glass stop-cock, the tube of which reached half-way down the neck of the flask, which was connected with the lower end of

* Phil. Trans., Vol. 162, p. 111.

† Journ. Chem. Soc., N. S., vol. xiii. p. 306.

‡ Compt. Rend., tom. liv. p. 1241.

§ Journ. Chem. Soc., vol. xvi. p. 216.

a reversed LIEBIG'S condenser. As the hydrobromic acid which is evolved during the reaction carries off some of the volatile hydrocarbons, the upper end of the condenser was bent downwards and connected with a flask containing a solution of caustic potash, in which, however, the tube did not dip, as if that had been the case, the liquid would have been sucked back into the hydrocarbon when the reaction slackened; one absorption flask was found sufficient to condense the hydrobromic acid completely. To ascertain, in the beginning of each experiment, whether all parts of the apparatus were tight, the cork of the flasks containing the soda solution was provided with a bent tube dipping into a little water.

I. *Normal Hexane.*

About 300 cub. centims. were heated in the large flask, and when briskly boiling, the stop-cock of the funnel-tube containing the bromine was so far turned that the liquid running down the tube was completely converted into vapour. On a bright day the colour of the bromine disappeared at once; on a dull day, however, the action was much slower and ceased altogether in gas-light. It was very curious to observe how, on a clear day, when the sun was suddenly obscured by dark clouds, the flask became filled with brown vapours, which disappeared again as quickly as the clouds before the sun.

The action was stopped before one-half of the hydrocarbon was attacked, and the product shaken with solid caustic potash, to free it from hydrobromic acid. On distilling, the excess of hexane came over first; the thermometer then began to rise, but even below 100° decomposition commenced, hydrobromic acid being evolved and a brominated liquid distilling over, while a black mass was left behind. In order to prevent this decomposition another portion was distilled with steam, but with no better success; a tarry or carbonaceous matter was left behind, and the distillate contained besides hexane, brominated hexane, hexene, and hydrobromic acid.

On submitting the brominated product to fractional distillation some of it began to decompose again, with the evolution of hydrobromic acid and blackening. But on continuing the distillations this decomposition gradually ceased, and a large quantity of a colourless liquid, boiling at 143—145°, and having a pungent and aromatic smell, could be isolated without difficulty. The low boiling point shows that this body was not primary hexyl bromide, which boils at 155·5°.* Besides it, a small quantity of a higher boiling liquid was obtained, which, however, by further distillations yielded some more of the bromide boiling at 143—145°, while the highest boiling portion completely decomposed. The fractions distilling between 68° (the boiling point of hexane) and 143° were very small, and consisted of mixtures of the hydrocarbon and the bromide, of which some more could be isolated by carrying on the distillation.

The hexyl bromide was decomposed by heating it in sealed tubes with potassium

* Lieben and Janecek, Liebig's Ann., 187, p. 126.

acetate and glacial acetic acid; the reaction commenced at 100°, proceeded rapidly at 120°, but to ensure a complete decomposition it was found necessary to heat to 150°.

The product consisted of a hexyl acetate and a little hexene, which were readily separated by distillation. The acetate possesses the characteristic smell of the acetic ethers, and boils at 146—150°; it was converted into the alcohol by heating it with caustic potash and a little water; the hexyl alcohol thus formed boiled, after drying it over potassium carbonate and removing a little hexene by distillation, at 136—140°, and smelled like methylbutyl carbinol. It was oxidised in the cold by chromic acid solution in the manner described in my last paper. A neutral liquid was thus obtained possessing the odour of methylbutyl ketone; it began to boil at 127°, and the greater portion distilled between this temperature and 130°; the thermometer then rose rapidly, and the residue had the odour of a compound ether, and consisted, as the following experiments show, undoubtedly, of hexyl butyrate. Besides these compounds a very small quantity of acids had also been formed which, judging by the smell, consisted of acetic acid and butyric acid; a few drops of dilute soda were sufficient to neutralise them.

The ketone and ether were again mixed and heated with the oxidising mixture, which contained twice as much water as in my previous experiments, nearly to the boiling point, and the acids converted in the sodium salts, as described in my former paper. Two series of experiments were made to ascertain their composition.

As it appeared very probable that only acetic acid and butyric acid were formed, the sodium salts were distilled with sulphuric acid and a little water, and the distillate after diluting with much water repeatedly distilled, the first distillates and the residues being kept separately. The first distillate and the last residue were then converted into the silver-salts by boiling them with silver carbonate, and the silver determined by ignition.

0·3241 of salt from the first distillate, crystallising in small needles, gave 0·1793 silver.

Calculated for silver butyrate.	Found.
55·38 per cent. Ag	55·32

0·2647 of salt from the last residue, forming larger glistening needles, gave 0·1690 silver.

Calculated for silver acetate.	Found.
64·67 per cent. Ag	63·84

The intermediate distillates were again mixed and neutralised with sodium carbonate. The acids were liberated from this mixture in four fractions by the method formerly described :—

	Salt.	Silver.	Per cent. Ag.
(1) Fraction—Indistinct needles	0·1892	0·1045	55·23
(2) „ Small needles	0·1091	0·0612	56·09
(3) „ „ „	0·2176	0·1290	59·29
(4) „ „ „	0·1842	0·1182	64·17

A portion of the first distillate was also converted into the calcium-salt, which gave the characteristic reactions of normal calcium butyrate.

From these experiments it follows that by the action of bromine on normal hexane, the secondary hexyl bromide,

$$\left.\begin{matrix} C_4H_9 \\ CH_3 \end{matrix}\right\} CH\,Br$$

or *methyl-butyl-carbyl bromide* is formed.

II. *Normal Heptane.*

This hydrocarbon is more readily attacked by bromine than hexane, and the reaction goes on, but of course very slowly, in artificial light. This is probably due to the higher temperature at which the substitution takes place. The phenomena are however in both cases quite similar. A portion of the product is decomposed by distillation, carbonaceous matter, hydrobromic acid, and heptene being formed, and a heptyl bromide distilling between 165—167° is obtained, having a pungent and aromatic odour.

It was analysed with the following result :—

0·326 gave 0·3414 silver bromide.

Calculated.	Found.
44·67 per cent. Br.	44·57

On converting it into the acetate a little heptene was formed ; the pure acetate boils at 169—171°, and has a pleasant fruity odour. By heating it with caustic potash a little heptene was again obtained, and secondary heptyl alcohol or *methyl-pentyl carbinol*,

$$\left.\begin{matrix} C_5H_{11} \\ CH_3 \end{matrix}\right\} CH\cdot OH.$$

This alcohol boils at 155—157°, and yields on oxidation in the cold methylpentyl ketone boiling at 150—152°, and a higher boiling compound ether. The products are converted by further oxidation into normal pentylic acid and acetic acid, as the following analyses of the silver salts show :—

		Calculated for silver pentylate 51·67.		
		Salt.	Silver.	Per cent. Ag.
(1)	Fraction—Small woolly needles ..	0·0741	0·0351	49·16
(2)	„ „ „ „ ..	0·1261	0·0649	51·48
(3)	„ „ „ „ ..	0·1795	0·0943	52·53
(4)	„ „ „ „ ..	0·2591	0·1448	55·89
(5)	„ „ „ „ ..	0·2623	0·1668	63·59
(6)	„ Glistening needles ..	0·2716	0·1741	64·10
	Calculated for silver acetate ..			64·67

The analysis of the first fraction differs from the calculated percentage 1·5 per cent. This is easily explained. I have already shown that the petroleum from which the heptane was obtained contains also an isoctane C_8H_{18} boiling only 15° higher than normal heptane. The latter undoubtedly contains some of the former, and its presence gives rise to the formation of a fatty acid containing more carbon than pentylic acid.

That the latter acid is the normal compound was proved by converting it into calcium pentylate; a cold saturated solution of this salt deposits on heating small glistening plates, which, after cooling, gradually dissolve again.

As result of this investigation it appears that by the action of bromine on normal paraffins only secondary bromides of the general formula,

$$\left.\begin{matrix} C_n H_{2n+1} \\ CH_3 \end{matrix}\right\} CH\,Br$$

are produced, but not a trace of primary bromide, or that the methyl groups which are present in these hydrocarbons, and which are readily attacked by chlorine, are not touched by bromine at all.

In addition to the secondary bromides other products are formed, which on distillation either decompose completely, or are resolved into hydrobromic acid and non-saturated hydrocarbons, which are probably olefines. The formation of these may be explained by assuming that besides the secondary bromides which I have described, others, which the theory indicates, are also formed, and that the latter, by the action of heat, split up into an olefine and hydrobromic acid. I have endeavoured to isolate these olefines, which I obtained mixed with paraffins, by adding bromine very carefully to the well-cooled mixture as long as its colour disappeared. The liquid, after being shaken with solid potash to remove free bromine and a little hydrobromic acid, was distilled by itself and with steam, but in both cases the bromides underwent complete decomposition, with the formation of a black mass and hydrobromic acid.

I hope, however, by continuing this research, to ascertain the nature of the products which are formed together with the volatile bromides.

V. *Experimental Researches on the Electric Discharge with the Chloride of Silver Battery.*

By Warren De La Rue, *M.A., D.C.L., F.R.S., and* Hugo W. Müller, *Ph.D., F.R.S.*

Received August 23,—Read December 13, 1877.

[Plates 6–8.]

Part I.—THE DISCHARGE AT ORDINARY ATMOSPHERIC PRESSURES.

In the 'Journal of the Chemical Society,' November, 1868,* we first published an account of the chloride of silver battery, which we had devised as one of great constancy and well suited for studying the discharge in exhausted tubes; we shortly afterwards carried the number of cells to 200, and presented a battery of 100, part of the 200, to our friend the late Mr. Gassiot, who at that time was in search of a constant battery suitable to his investigations. Mr. Gassiot did not, however, adopt the chloride of silver battery, and it remained unemployed until 1874, when, in pursuance of a suggestion of our friend Mr. Spottiswoode, we put together for his use 1080 cells, but soon found that in order to effectually study the phenomena of the discharge it would be necessary to carry the number of cells much higher, this we have gradually done, and now possess 8040 cells in actual work, and 2680 more completed but not charged with fluid†. Amongst the 8040 cells in actual use are the first 1080 constructed in 1874, so that the constancy of the battery is thereby fully established. In the course of the increase of numbers, experience has led to many modifications of the details of the battery, but we reserve for the latter part of this communication a description of them. On the 24th February, 1875‡, we gave an account, in conjunction with our friend Mr. Spottiswoode, of some experiments made with 1080 cells, and on the 28th April, 1875, we made a verbal communication to the Society of Telegraph Engineers, when the battery of 1080 cells was exhibited.§ Subsequent to that meeting, our friend Mr. Latimer Clark, called our attention to and lent us a small work entitled 'The Electric Telegraph in British India,' by W. B. O'Shaughnessy, M.D., F.R.S., London, 1853, where, at page 14, the author describes an experimental cell of fused chloride of silver, and in justice to him we

* Journ. Chem. Soc., new series, vol. vi.; entire series, vol. xxi. p. 488.

† January 1, 1878.—The extra number now made up and charged is 2960 cells, which brings the total up to 11,000 cells. See Supplement, p. 116.

‡ Proc. Roy. Soc., vol. xxiii. p. 356. 1875.

§ Journ. Tel. Engineers, vol. iv., No. XI., p. 202. 1876.

mention this circumstance; at the same time, we must say that the use of chloride of silver for a battery was an independent thought on our part. Dr. O'Shaughnessy does not appear to have developed the idea into a workable battery, although he stated in his book that it would be of value for local circuits in signalling.

In October, 1875,* we made a communication to the Académie des Sciences of Paris, including some photographs of the stratified discharge obtained the 3rd of the previous month of August;† also a further communication to the Royal Society in 1876,‡ on the length of the spark with 600, 1200, 1800, 2400 rod cells, and subsequently, in May, 1877, a short statement of the relative length of the spark in different gases at the ordinary atmospheric pressure.§

Although we do not pretend to have solved the problem of the cause of stratification in tubes exhausted to a great extent of the gases they originally contained, we venture to think that an account of our experiments will to some extent limit the field of future inquiry, and that they may have present interest for the electrician.

We propose in the first place to deal with the discharge at ordinary atmospheric pressures, and in order that the requisite data for comparison with the results of other experimenters may be at hand, we here give the electro-motive force of our battery.

The following value was obtained by balancing a battery of 10 chloride of silver rod cells against 1 Latimer Clark standard mercurial cell‖ (1·457 volt.). The chloride of silver battery was kept continuously working through a high resistance, and the standard cell only opposed it when the comparison had to be made.

The zinc of a battery of 10 rod chloride of silver cells, and the zinc of a Latimer Clark cell were connected together and to one end of a resistance of 9270 ohms. The silver of the battery of 10 cells was connected to the other end of the resistance coils. The mercury of the Clark cell was connected to one terminal of a Thomson galvanometer, the other terminal of which was connected to a shifting contact plug. It was found that there was no deflection of the galvanometer when this plug was inserted at 1275. Consequently

$$\frac{\text{EMF of 1 Ag Cl cell}}{\text{EMF of 1 Lat. Clark cell}} = \frac{9270}{1275 \times 10} = 0{\cdot}7271,$$

$$\text{Or, EMF of 1 Ag Cl cell} = 0{\cdot}7271 \times 1{\cdot}457 = 1{\cdot}059 \text{ volt.}$$

* Comptes Rendus, No. 16, p. 686, and No. 17, p. 746. 1875.
† A fac-simile of one of these will be given in Part II.
‡ Proc. Roy. Soc., vol. xxiv. p. 167. 1876.
§ Proc. Roy. Soc., vol. xxvi. p. 227.
‖ Phil. Trans., vol. 164, p.

Another comparison with 20 cells gave a value of 1·002 volt, II.; a comparison made by Dr. MUIRHEAD in 1875, gave 1·031 volt, III.

Electro-motive force of the chloride of silver cell is consequently:

	volt.
I.	1·059
II.	1·002
III.	1·031
Mean	1·03

In all succeeding calculations we have taken the electro-motive force as—

$$1\cdot03 \text{ volt} = \frac{1\cdot03 \times 10^8}{3 \times 10^{10}} = \cdot00343 \text{ electro-static unit.}$$

The internal resistance of the battery depends partly on the distance between the zinc rod and the chloride of silver, but mainly upon the circumstance of the chloride of silver being used in the form of powder or fused into rods; we have 3240 powder-cells and 4800 rod-cells in work; gradually and after many months the internal resistance increases in consequence of a hard skin of oxychloride of zinc forming on the zinc rods. We have taken 5 ohms for the internal resistance of the rod, and 15 ohms as that of the powder-cells in the succeeding calculations.

We have determined the electro-motive force of the two other haloïd compounds of silver, and find it to be as under for the three haloïds—

	volt.
Chloride of silver	1·03
Bromide „	0·908
Iodide „	0·758

To measure the striking distance at ordinary atmospheric pressures, we have used the discharger figured below, which was made from our drawings by our assistant, Mr. JAMES FRAM, who has aided us materially during this investigation by his intelligent interpretation of our wishes, and his mechanical skill in carrying them out.

The frame work is of ebonite, and its construction sufficiently obvious; the screw S having a $\frac{1}{80}$th of-an-inch thread, has a cylindrical recess at the lower end into which is inserted one of the terminals to be used in the experiments (in this case a point P); the end of the screw has four slits cut through it, in order that it may be contracted and made to pinch tightly any terminal inserted in it by means of the binding-nut N, working on the end of the screw, which is slightly conical but still has a full thread cut upon it. The nut fixed in the cross head at the top of the frame through which the screw works is in metallic communication with the clamp C, and is divided horizontally into two parts which are pressed asunder by three spiral springs in order to prevent shake or play of the micrometer screw. At the base of the

instrument is a fixed holder with a screw and binding-nut like that for the upper terminal, this is in metallic communication with the clamp C′, and holds in the above figure a terminal in the form of a disc D. To the top of the screw is fixed the ebonite wheel A, to which is fastened a metallic ring divided into 20 parts, each representing $\frac{1}{1000}$th of an inch; as the divisions are 0·35 inch apart at the outer periphery of the disc, it will be obvious that the $\frac{1}{10000}$ may be approximately estimated without difficulty. On the top of the right-hand pillar is a vertical scale by which the number of whole revolutions of the screw is read off. Before com-

Fig. 1.

mencing an experiment the discharger is connected with a battery of 10 cells through a detector-galvanometer, and the terminals approached cautiously until the motion of the galvanometer indicates contact; the length of the spark of 10 cells is so small that the reading of the micrometer is taken as zero. The screw is run up for a greater distance than the anticipated length of the spark to be measured, and when the micrometer has been connected with the battery it is gradually approached by steps.

The connexion between the micrometer-discharger and the battery is effected by means of the discharging key, shown in the figures 2 and 3, which we have designed specially for our battery, as the ordinary form of doubly reversing key, even when made much larger than usual, was found not to answer for the high potentials we employ, in consequence of the voltaic arc continuing the current after metallic contact had been broken.

The battery is connected to the discharging key at the insulated standards in

which the horizontal ebonite axis A Z works, to this is fixed the ebonite handle H; there are metallic collars A and Z, carrying the pivots, fitted on the ebonite axis. These pivots are in metallic communication, by means of leading wires inserted in the ebonite axis, respectively with the spring pieces S and S′, in which are inserted renewable platinum wires held in their places by binding-nuts. The four bracket standards B B, B′ B′, are connected with the apparatus through which the discharge

Fig. 2.

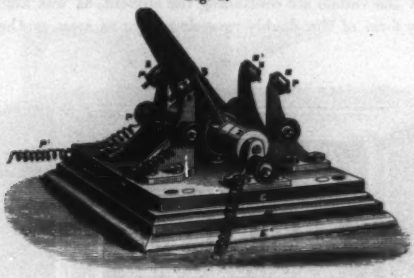
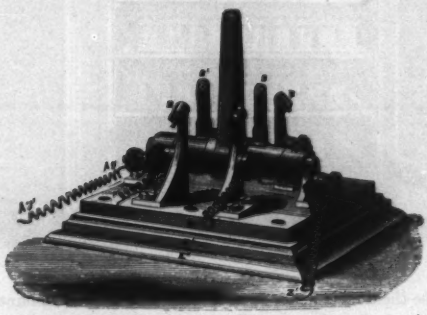


Fig. 3.



is to be made by means of the wires N′ and P′. The bracket standards, B B, and B′ B′, are connected together respectively by means of diagonal wires below the top ebonite plate E, the middle ebonite plate E′, half an inch thick, intervening between them. These bracket pieces have adjustable platinum contact wires screwed through their heads and held in position by binding-nuts. The horizontal axis carrying the spring contact pieces S S′, is held in its place by a strong spring

ending in a V piece, underneath and parallel with it, which falls into one of three notches to hold it out of contact when the handle H is upright, as in fig. 3, or in contact to the right, or to the left as shown in fig 2.

After the adjustment of the distance between the terminals of the discharger, fig. 1, the current was usually sent alternately so as to make the upper terminal positive or negative by means of the discharging key just described, so that the striking distance was obtained for the current in both directions; on breaking contact with this key there is no fear of the voltaic arc continuing the current, as was found to be the case with the ordinary form of the doubly reversing keys as soon as the battery reached

Fig. 4.

4000 cells, because the double distance of B′ to S′ and S to B amounts to $2\frac{1}{2}$ inches; and it has been found that the arc will not extend after separation of the terminals to more than $1\frac{1}{2}$ inch even when the battery consists of 8040 cells.

All the wires leading from the batteries are 0·0625 ($\frac{1}{16}$th) inch diameter, and are covered with a coating of gutta percha 0·125 ($\frac{1}{8}$th) inch thick; the wires as they run round the laboratory are supported on ebonite supports in order, as far as possible, to prevent leakage. The batteries are arranged in cabinets standing on ebonite feet (E, fig. 4), and each tray of 20 also stands on ebonite feet.

Fig. 4 shows a cabinet 4 feet 7½ inches (140·9 centims.) high, 3 feet 6 inches (106·7 centims.) wide, and 17 inches (43·17 centims.) deep, inside measurement, containing a battery of 1200 rod-cells, each tray holding 20 cells; all the wires represented are covered with gutta percha, and when they connect shelf to shelf they pass through ebonite cylinders fixed in the shelves. Inside the case on the right is fixed a switch, as represented in figs. 5 and 6.

Fig. 5.

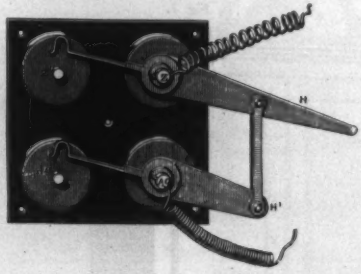
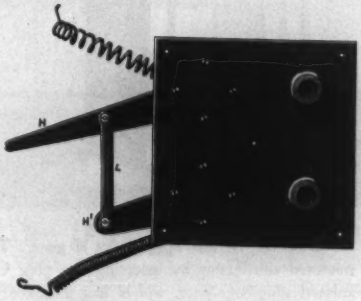


Fig. 6.

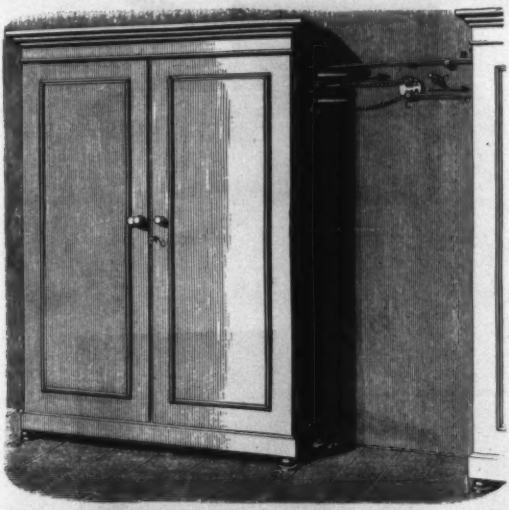


The frame work and the levers H and H′ are of ebonite; the terminal wires from the battery are connected to the axes of the lever handles Ag and Z respectively; when the battery is not required the levers rest in the position shown in the figures, when it is to be brought into circuit the handle H is elevated so as to bring the brass spring pieces in contact with the brass rods Z′ and Ag′ which pass to the outside of the cabinet, the outer ends of the rods are hollow in order to admit of the insertion

of contact plugs (h and h', fig. 7). Fig. 6 shows that face of the switch which is screwed against the inside of the case.

Fig. 7 shows the means of connecting up the several batteries. The battery on the left being represented in circuit by the insertion of brass plugs with ebonite handles h, h', into the cylindrical hollow ends of the switch rods; when this battery is not in use the plugs are withdrawn and inserted into the supports shown in the figure attached to the end of the case, it being understood that the handle of the switch

Fig. 7.



has been depressed to throw the contact springs out of gear. The conducting wire has moreover to be rendered continuous by inserting the plug C between the jaws Z and A of the insulated plug-connector, which has a space of ·625 ($\frac{5}{8}$th) inch between the nearest points of the jaws, a distance absolutely necessary with batteries of such high tension as those we have in action.

For special experiments we have found it necessary to design and have constructed a commutator capable of reversing the current many times in a second, that shown in fig. 8 represents the form we have found most convenient to employ; it is capable of reversing the current 352 times in a second when the handle is turned 240 times in a minute, which it is not difficult to do. It will be seen that each

revolution of A, B, C, D reverses twice. This piece of apparatus follows the discharging key, figs. 2 and 3, in order from the poles of the battery, the wire A*g* being in connexion with the bracket B, and the wire Z with B′ of the contact key, fig. 2.

The figure is so distinct as scarcely to require any description; it will be seen

Fig. 8.

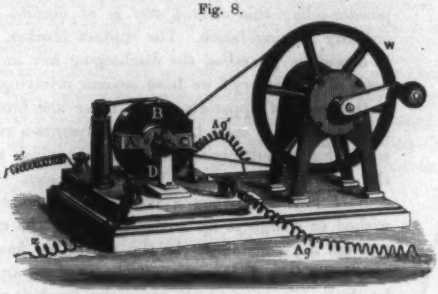
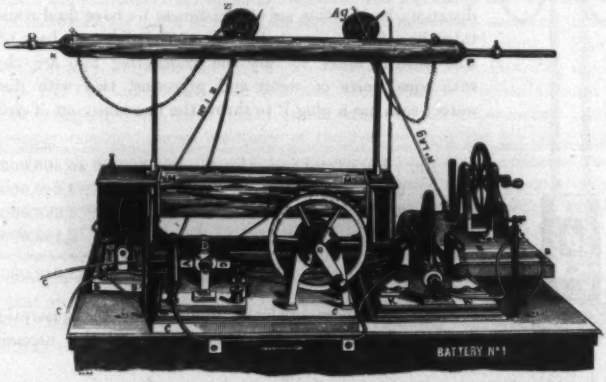


Fig. 9.

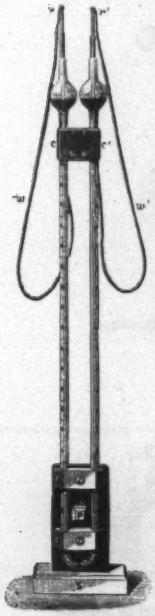


that B and D are of one piece of metal, and also A and C of another, the spring conductors making contact at 90° distance from each other; each of the uprights supporting the axis of the revolving disc is in metallic connexion with its respective insulated clamp. In the position shown in the figure the positive current passes from A*g* to the upright supporting the axis of the revolving disc and through the

right hand spring to the wire Ag'; the negative current from Z to the upright on the other side of the revolving disc, only partly seen, thence through the upper spring to Z'.

Besides this we have a contact breaker very similar in appearance, and shown *in situ* in fig. 9 on the top of the dwarf cabinet of battery No. 1, containing 1080 powder-cells; this cabinet top is of ebonite and forms our ordinary working bench. The contact breaker, B B, is placed in a position preceding the discharging key in order from the poles of the battery; we have several revolving discs belonging to this piece of apparatus which make and break from 352 to 2112 times in a second. M M′ represents a revolving mirror, which has a multiplying wheel, and in which the reflection of the discharge in a vacuum tube can be seen. S S′ is a short contact key used when a condenser is employed, and it is wished to charge it up without causing the current to pass through any resistance. In the circuit we have a set of coil-resistances from 1 to 1,000,000 ohms; these are specially insulated, the wires running in grooves on insulating cylinders made of paraffined cardboard, in order that they may be kept at a distance; besides this set of resistances we have fluid resistance tubes like that represented in fig. 10; all but one have adjustable wires in order to vary the resistance; two are charged with equal parts of water and glycerine, two with distilled water; each has a plug P to throw the resistance out of circuit.

Fig. 10.



	ohms.
No. 1 has a total approximate resistance of	30,500,000
„ 2 „ „ „	4,000,000
„ 3 „ „ „	2,690,000
„ 4 „ „ „	6,150,000
Total fluid resistances	43,340,000

These resistances gradually diminish by the absorption of ammoniacal salts from the atmosphere, and this necessitates occasionally the entire renewal of the fluid.

We have two tangent galvanometers of different degrees of sensitiveness specially insulated, which can be put in circuit by the withdrawal of two plugs, and also an induction coil, the primary of which may be brought into circuit; it is No. 819 of Apps's make, the particulars of which are as follow:—

	Length of wire. miles.	Diam. of wire. inches.	Resistance. ohms.	Turns.	Layers.
Primary .	1	·014	316	12,958	31
Secondary .	4	·0033	19,355	18,260	22

This we call a detector-coil, it being used to render evident pulsations in the current, and it will be referred to hereafter. The secondary wire of the coil is led to a delicate THOMSON galvanometer.

All these pieces of apparatus can be plugged out of circuit, when not required, in a few seconds, and each battery can be as readily brought into or thrown out of action without inconvenience or danger to the operator. Not without fear of being prolix, it has appeared to us desirable to commence by giving the preceding details, as it will facilitate the understanding of the varied experiments we have to describe hereinafter. We will commence with—

1*st. Discharge at ordinary Atmospheric Pressures.*

The discharge from a point presents many interesting features, which do not occur with other shaped terminals, which we will describe later on, page 88, and at once proceed to the discharge from spherical surfaces, first premising that we have found that the nature of the metal employed for terminals in most cases makes no difference whatever in the length of the spark (*distance explosive*) of the battery. Whatever may be the theory of the electric discharge, our experiments show that with the same terminals and the same number of cells the results have a remarkable constancy, notwithstanding the length of the interval between the experiments, and the consequently varying internal resistance of the battery from the gradual formation of the skin of oxychloride of zinc before referred to, and hereinafter to be specially discussed. *The length of the spark evidently depends essentially on the number of cells and their electro-motive force.* The spherical surfaces we have employed are of brass, 1·5 inch in diameter and having a radius of 3 inches. The discharging-micrometer (fig. 1) does not permit larger terminals to be used, but there is no reason to suppose that their diameter materially affects the results, because we found that spherical surfaces smaller in diameter gave nearly the same numbers. In evidence of the constancy of the results, we give the following numbers, some of which will be dealt with in deducing the length of spark for a given number of volts.

STRIKING distance between two spherical surfaces each 1·5 inch in diameter, the radius of curvature being 3 inches.

1080 CELLS.		1200 CELLS.		2160 CELLS.	
	inch.		inch.		inch.
1876. Feb. 24*	0·00750	1876. June 9	0·00600	1876. Feb. 24	0·0145
	0·00600		0·00575		0·0143
	0·00500		0·00575		0·0143
	0·00500		0·00575		0·0143
	0·00450		0·00600	Oct. 20	0·0142
	0·00450	June 10	0·00550		0·0142
	0·00480		0·00575		0·0142
	0·00500		0·00600		0·0142
June 9	0·00475		0·00625		0·0144
	0·00450	1877. June 5	0·00650		0·0148
	0·00425		0·00600		
June 10	0·00450				
	0·00475				
	0·00450				
Oct. 20	0·00425				
	0·00425				
	0·00425				
	0·00440				
	0·00440				
	0·00440				
	0·00440				
	0·00440				

2400 CELLS.		3240 CELLS.		3600 CELLS.	
	inch.		inch.		inch.
1876. June 9	0·0170	1876. Feb. 2	0·02430	1876. June 9	0·030
	0·0170		0·02550		0·030
	0·0170		0·02550	June 10	0·030
	0·0170	Oct. 20	0·02525		0·030
	0·0170		0·02525	1877. June 5	0·029
	0·0170		0·02525		
June 10	0·0175		0·02524		
	0·0180		0·02524		
1877. June 5	0·0160				

4320 CELLS.		4800 CELLS.		5400 CELLS.	
	inch.		inch.		inch.
1876. Feb. 24	0·0360	1876. June 9	0·04400	1876. Feb. 24	0·0490
	0·0375		0·04400	Oct. 20	0·0490
Oct. 20	0·0370	June 10	0·04375		0·0495
	0·0372	1877. June 5	0·04300		0·0500
	0·0375				
	0·0375				

* Here and elsewhere throughout this paper, except where the contrary is expressly stated, it is to be understood that the different observations recorded for the same date were obtained with different batteries.

5880 CELLS.	inch.	6960 CELLS.	inch.	8040 CELLS.	inch.
1876. June 9	0·057	1876. June 9	0·0700	1876. June 8	0·08500
June 10	0·056	June 10	0·0705	June 9	0·08200
1877. June 5	0·054	1877. June 5	0·0665		0·08300
				June 10	0·08300
				Oct. 20	0·08225
				1877. May 15	0·08200
				May 16	0·08200
					0·08400
				June 5	0·08000

The following numbers were obtained at different dates with the batteries combined in various ways :—

STRIKING distance between two spherical surfaces, 3 inches radius and 1·5 inch diameter.

Date.	No. of cells.	Striking distance. inch.	Curve.
Feb. 24, 1876	1080	0·00560	
	2160	0·01435	
	3240	0·02510	I.
	4320	0·03675	
	5400	0·04900	
June 9, 1876	1200	0·00600	
	2400	0·01700	
	3600	0·03000	
	4800	0·04400	II.
	5880	0·05700	
	6960	0·07000	
	8040	0·08300	
June 10, 1876	1200	0·00585	
	2400	0·01775	
	3600	0·03000	
	4800	0·04375	III.
	5880	0·05600	
	6960	0·07050	
	8040	0·08300	
Oct. 20, 1876	1080	0·00434	
	2160	0·01433	
	3240	0·02537	
	4320	0·03730	
	5400	0·04950	IV.
	6480	0·06288	
	7560	0·07550	
	8040	0·08225	
June 5, 1877	1200	0·00625	
	2400	0·01600	
	3600	0·02900	
	4800	0·04300	V.
	5880	0·05400	
	6960	0·06650	
	8040	0·08000	

Two spherical surfaces, 0·75 inch radius, diameters 0·4 and 0·55 inch respectively.

Date.	No. of cells.	Striking distance. inch.	Curve.
Feb. 12, 1876	600	0·00120	VI.
	1200	0·00350	
	1800	0·00930	
	2400	0·01400	
Jan. 13, 1876	1080	0·00425	VII.
	2160	0·01325	
	3240	0·02200	
	4320	0·03500	
	5400	0·04600	

These numbers were plotted down on paper ruled in millimeters, the abscissæ representing the number of cells (50 millimeters to 1000 cells) and the ordinates the striking distance (40 millimeters to ·01 inch). With the curves drawn to this scale, it was practicable to estimate to the $\frac{1}{100000}$ of an inch.

The following striking distances were obtained by reading off the ordinates at the various numbers of cells given in Table I. :—

TABLE I.

From curve	No. of cells.											
	250	500	1000	1500	2000	2500	3000	4000	5000	6000	7000	8000
I.	0·00125	0·00252	0·00525	0·00920	0·01312	0·01775	0·02275	0·03325	0·04433	—	—	—
II.	0·00125	0·00243	0·00480	0·00850	0·01325	0·01800	0·02330	0·03458	0·04625	0·05833	0·07025	0·08250
III.	0·00125	0·00250	0·00480	0·00875	0·01875	0·01900	0·02380	0·03460	0·04575	0·05750	0·07075	0·08250
IV.	0·00100	0·00200	0·00400	0·00825	0·01275	0·01775	0·02230	0·03400	0·04500	0·05678	0·06900	0·08150
V.	0·00125	0·00250	0·00512	0·00850	0·01275	0·01700	0·02250	0·03360	0·04485	0·05525	0·06700	0·07950
VII.	0·00100	0·00200	0·00385	0·00775	0·01118	0·01600	0·02000	0·03100	0·04175	—	—	—
Means	0·00117	0·00233	0·00464	0·00849	0·01280	0·01758	0·02244	0·03353	0·04465	0·05696	0·06925	0·08150
VIII.	0·00125	0·00225	0·00500	0·00846	0·01275	0·01752	0·02300	0·03350	0·04512	0·05700	0·06930	0·08180

We were led to adopt the numbers given at VIII. as more nearly representing a true mean curve, the judgment being guided by an inspection of the several curves representing the individual observations (Plate 6).

Curve VIII., it will be seen, runs very smoothly and tends to show that up to a difference of potential of 8000 cells there is not any common factor which can be used as a multiplier to furnish the striking distance for a given number of cells; for the differences between the striking distances of consecutive equal numbers of cells is an increasing quantity, the increment of increase is, however, very small after 4000 cells have been reached.

From the mean curve VIII. the following *ratios* for a given number of cells were obtained :—

TABLE II.

Difference of potential in chloride of silver cells.	Striking distance. inch.	Ratios.	Difference.	Difference per 1000 cells.
250	0·00125	1,000		
			800	
500	0·00225	1,800		4,000
			2,200	
1000	0·00500	4,000		
			2,769	
1500	0·00846	6,769		6,200
			3,431	
2000	0·01275	10,200		
			3,802	
2500	0·01752	14,002		8,200
			4,398	
3000	0·02300	18,400		
			8,400	
4000	0·03350	26,800		8,400
			9,300	
5000	0·04512	36,100		9,300
			9,500	
6000	0·05700	45,600		9,500
			9,840	
7000	0·06930	55,440		9,840
			10,010	
8000	0·08180	65,450		10,010

With the mean curve VIII. it was also easy to derive numbers for volts instead of chloride of silver cells; thus the following Table III. shows difference of potential in volts requisite to obtain a spark in air at ordinary atmospheric pressures between the spherical surfaces of 3 inches radius and 1·5 in diameter.

TABLE III.

Volts.	Striking distance. inch.	Differences.	Between volts.	Additional length of spark for 1000 additional volts. inch.
250	0·00100			
		125	0	
500	0·00225			
		125	and	0·00482
750	0·00350			
		132	*	
1000	0·00482		1000	
		338		
1500	0·00820		and	0·00751
		413		
2000	0·01233		2000	
		467		
2500	0·01700		and	0·00967
		500		
3000	0·02200		3000	
		500		
3500	0·02700		and	0·01025
		525		
4000	0·03225		4000	
		550		
4500	0·03775		and	0·01100
		550		
5000	0·04325		5000	
		575		
5500*	0·04900		and	0·01135
		560		
6000	0·05460		6000	
		610		
6500	0·06070		and	0·01190
		580		
7000	0·06650		7000	
		600		
7500	0·07250		and	0·01200
		602		
8000	0·07852		8000	

It appears that after a difference of potential 2000 volts has been reached, each additional increment of 1000 gives about the same additional length to the spark, but not exactly so, as each succeeding number is slightly in excess of its predecessor up to 8000 volts at all events; so that the striking distance for 8000 is 16·29 times that for 1000.

In December, 1859, and in the first four months of 1860, experiments were made under the direction of Sir WILLIAM THOMSON with the object of determining "the electro-motive force required to produce a spark." An account of these experiments was presented to the Royal Society by Sir WILLIAM THOMSON, and published in the Proceedings.† It appears from this account that a condenser was used which might be

* This agrees with Sir WILLIAM THOMSON's conclusion (Proc. Roy. Soc., vol. x. p. 338), "that a DANIELL's battery of 5510 elements can produce a spark between two slightly convex metallic surfaces at $\frac{1}{10}$th of an inch asunder in ordinary atmospheric air."

† Proc. Roy. Soc., vol. x. pp. 326–338, 1860.

charged to any potential measurable by Sir WILLIAM THOMSON's absolute or his portable electrometer, the opposite plates of the condenser being connected to two very slightly convex surfaces, which might be adjusted to any required distance from each other. For the readiness of comparison with our own results, we have reduced into volts (Table IV.) Sir WILLIAM THOMSON's numbers, contained in his most recent communication on the subject, and given in electro-static measurements, taking for v (the ratio of an electro-magnetic to an electro-static unit) the value of 3×10^{10}, and for a volt the value 10^8 C.G.S. unit of potential.

TABLE IV.

Inch.	Centimetres.	Electro-static force or EMF per centimetre.	Difference of potential of the opposite surfaces.	EMF in volts = electro-magnetic unitsdivided by 10^8.	Difference of potential in volts per centimetre.
0·0034	0·0086	267·1	2·30	690	80,230
0·0050	0·0127	257·0	3·26	978	77,000
0·0060	0·0152	262·0	3·33	999	78,660
0·0075	0·0190	224·0	4·26	1278	67,260
0·0111	0·0281	200·6	5·64	1692	60,220
0·0161	0·0408	151·5	6·18	1854	45,450
0·0222	0·0563	144·1	8·11	2433	43,210
0·0230	0·0584	139·6	8·15	2445	41,870
0·0271	0·0688	140·8	9·69	2907	42,250
0·0356	0·0904	134·9	12·20	3660	40,490
0·0416	0·1056	132·1	13·95	4185	39,630
0·0522	0·1325	131·0	17·36	5208	39,310

TABLE V.—Mean results obtained with the AgCl battery, 1876. Feb. 24, June 9th and 10th, Oct. 19th and 20th.

Inch.	Centimetres.	EMF in AgCl cells.	EMF in volts.	Difference of potential in volts per centimetre.
0·00497	0·01263	1080	1113	88,060
0·00575	0·01461	1200	1236	84,590
0·01434	0·03642	2160	2225	61,090
0·01738	0·04414	2400	2472	56,010
0·02524	0·06410	3240	3336	52,050
0·03000	0·07619	3600	3708	48,660
0·03703	0·09404	4320	4449	47,320
0·04388	0·11440	4800	4943	43,210
0·04925	0·12510	5400	5562	44,460
0·05650	0·14350	5880	6056	42,210
0·06287	0·15970	6440	6674	41,780
0·07025	0·17840	6960	7168	40,180
0·07550	0·19170	7560	7785	40,160
0·08275	0·21010	8040	8281	39,420

Our results give a higher potential as requisite to produce a spark than the numbers of Sir WILLIAM THOMSON; for example, compare in Sir WILLIAM THOMSON's results 1278 volts, 67,260, with 1236 volts, 84,590, in our table; again, 5208 volts, 39,310, Sir WILLIAM THOMSON, with our numbers, 5562 volts, 44,460. In the first case our numbers are to Sir WILLIAM THOMSON's as 1·258 to 1, and in the second 1·131 to 1; that is, in the first case 26 and in the second 13 per cent. greater than his. But the accordance of some and the discordance of others of our results with those of Sir WILLIAM THOMSON is best illustrated by the curves on Plate 6, representing on a reduced scale (the abscissæ to $\frac{3}{4}$ths, the ordinates to $\frac{1}{2}$) the curves as originally laid down. Curves I., II., III., IV., V., VI., and VII. show the plotting down of the actual observations made by us; curve VIII. the mean curve of our results; IX. shows Sir WILLIAM THOMSON's; the first parts of VIII. and IX. are again given in curves VIII.^{a} and IX.^{a}, in the upper part of the plate, on the original unreduced scale. Sir WILLIAM THOMSON's first observation was made with a difference of potential of 690 volts, and his result agrees very closely with our own. This accordance holds good up to 1690 volts, his lengths of spark rising a little more rapidly for definite increments of electro-motive force than our own; but between 1692 volts, which gave a length of spark equal to 0·011 inch, and 1854 volts, which gave a spark of 0·016 inch, there is a remarkably sudden rise in Sir WILLIAM THOMSON's results, which is quite at variance with our experiments; from that point (1854 volts), however, the two curves are sensibly parallel up to the limit of his observations.

It must be remarked that, notwithstanding the accordances in the distances between the terminals, when the spark jumped in our oft-repeated experiments, it seldom occurred actually at the point of nearest approach, although it usually did so in close proximity with it. The distances observed for successive increments in the number of cells are, it will be seen, considerably less with spherical surfaces (not so much as a fourth in many cases) for high tensions than with a point and a disc, and moreover the increase of increment with spherical surfaces does not conform to the ratio of the square of the number of cells, as before referred to in a communication to the Society, and published in the Proceedings, vol. xxiv. p. 167, 1876.

The difference in our results with spherical surfaces of three inches radius of curvature and those of Sir WILLIAM THOMSON with very slightly curved surfaces, induced us to make other experiments, with some so nearly flat that at their peripheries (0·687 inch from the centre) the distance was about 0·004 inch when the centres touched. The following three series of observations were made, viz.:—

TABLE VI.—Showing the length of spark between two nearly flat surfaces.

Curve.	1200 cells.	2400 cells.	3600 cells.	4800 cells.	5880 cells.	6960 cells.	8040 cells.	
	inch.	inch.	inch.	inch.	inch.	inch.	inch.	
	0·014	0·021	0·031	0·049	0·059	0·075	0·089	June 25, 1877.
	0·011	0·023	0·033	0·051	0·058	0·073	0·086	June 26, 1877.
	0·011	0·018	0·033	0·047	0·058	0·072	0·090	June 26, 1877.
X. Mean	0·012	0·021	0·032	0·049	0·058	0·073	0·088	

The mean results are laid down in curve X., Plate 7, where curves VIII. and IX. are repeated from Plate 6 for the sake of comparison. By inspection of these curves it will be seen that curve X. is sensibly parallel with curve VIII., the lengths of spark with the planes being uniformly greater than those with the spherical surfaces. The mean values for 1200 and for 4800 cells are abnormally high; but this would cease to be the case if the observations 0·014 for 1200 cells, June 25th, and 0·051 for 4800 cells, June 26th, be neglected. Above 2400 cells the curve of the planes is intermediate between Sir WILLIAM THOMSON's (curve IX.) and our curve of the spherical surfaces (curve VIII.). Table VII. is given for comparison with Table III.

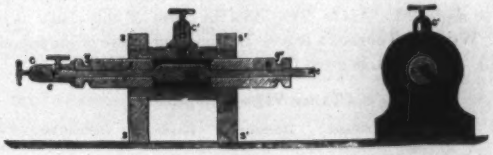
TABLE VII.—Two planes.

Volts.	Striking distance. inch.	Difference.	Between volt.	Additional length of spark for 1000 additional volts.
250	0·00233		0	
		242		
500	0·00475		250 and	0·00975
		250		
750	0·00725		1000	
		250		
1000	0·00975		1000	
		420		
1500	0·01400		and	0·00725
		300		
2000	0·01700		2000	
		325		
2500	0·02025		and	0·00825
		500		
3000	0·02525		3000	
		505		
3500	0·03030		and	0·01100
		595		
4000	0·03625		4000	
		675		
4500	0·04300		and	0·01305
		630		
5000	0·04930		5000	
		470		
5500	0·05400		and	0·00825
		355		
6000	0·05755		6000	
		620		
6500	0·06375		and	0·01245
		625		
7000	0·07000		7000	
		630		
7500	0·07630		and	0·01275
		645		
8000	0·08275		8000	

The striking distance is very little more for 8000 than eight times (8·487) that given for 1000, which may be too great for the reason stated in page 85.

On the suggestion of Professor E. Mascart, of the Collége de France, Paris, who honoured us with a visit to our laboratory in April, 1877, we have determined the striking distance between two concentric cylinders; fig. 11 shows the arrangement of the apparatus. S S, S′ S′ are two ebonite stands supporting the outer cylinder A A of brass, 2·5 inches long, and bored with a perfectly true hole, 0·4895 inch diameter; B is the inner cylinder, also of brass, which was turned at first nearly of the diameter of the hole of the outer cylinder; on its axis, of one piece with the cylinder, are fitted two ebonite cylinders E E, *exactly* fitting the hole; their outer ends have a groove

Fig. 11.



turned in them, in which the string of a hand-bow works to turn the cylinder on its centres c, c when it is wished to reduce it in size; C, C′ are clamps for connecting the outer and inner cylinder respectively with the battery. When it is wished to make the inner cylinder less in size, the clamp C is removed, and the cylinder is put on dead-centres, and made to rotate with the hand-bow, and reduced by turning off a very small quantity at a time between each trial of the striking distance; the quantity removed between each trial was generally 0·001 inch or less, and by this means the striking distance was ascertained to 0·0005 inch.

In the first instance the same cylinder was reduced to determine the limit of the striking distance for the several numbers of cells employed; on a repetition of the experiment, seven inner cylinders were turned to the size at which the spark just passed and retained; this delicate work was executed with great care and skill by Mr. Fram.

Table VIII.—Length of spark between two concentric cylinders.

Curve.	1200 cells. inch.	2400 cells. inch.	3600 cells. inch.	4800 cells. inch.	5880 cells. inch.	6960 cells. inch.	8040 cells. inch.	Date.
	0·0086	0·0248	0·0534	0·0655	0·0780	0·0897	0·0983	June 5, 1877.
	0·0093	0·0281	0·0451	0·0638	0·0711	0·0821	0·1015	June 29, 1877.
XI. Mean.	0·0089	0·0264	0·0492	0·0646	0·0746	0·0859	0·0998	Plate 7.

In taking the striking distances the current was reversed after a first trial, so as to

make the outer cylinder positive and negative alternately; in the majority of cases the longest spark was obtained with the outer cylinder positive. For the first 1200 cells the striking distance between two concentric cylinders is less, but after that number greater than between nearly flat surfaces, as will be seen by comparing the numbers given in Table VI. with those in Table VIII.*

From curve XI., Plate 7, the following ratios for a given number of volts were obtained.

* M. Gaugain, Annales de Chim. et de Physique, 4e série, T. VIII., pp. 115 to 118, has investigated the striking distance between two concentric cylinders, using, however, much higher potentials than we have employed. His experiments show that if the inner cylinder is kept constant and the number of elements and the diameter of the outer cylinder are increased or diminished, the density required to produce a spark does not change at the moment of the spark jumping. If the inner cylinder is increased or diminished in diameter, then the density is lessened or increased. Our results calculated in accordance with the formula

$$\mu = \frac{N}{r \log \frac{R}{r}}$$

where μ = density,
N = number of cells,
R = radius of outer cylinder,
r = radius of inner cylinder,

give the following numbers:

No. of Cells.	Length of Spark. Inches.	Density μ.
1200	0·0089	3163
2400	0·0264	2217
3600	0·0492	1889
4800	0·0646	2002
5880	0·0746	2190
6960	0·0859	2330
8040	0·0998	2438

From these results, and from our own with spherical and plane surfaces, as well as those of Sir W. Thomson, it is evident that the density is not constant for short lengths of spark (1200 cells); after that number it is pretty uniform, except in the case of 3600 cells, where it reaches a minimum.

TABLE IX.—Two concentric cylinders.

Volts.	Striking distance. inch.	Differences.	Between volts.	Additional length of spark for additional 1000 volts.
250	0·0017		0	
		16		
500	0·0033			
		17	and	0·0069
750	0·0050			
		19		
1000	0·0069		1000	
		52		
1500	0·0121		and	0·0121
		69		
2000	0·0190		2000	
		78		
2500	0·0268		and	0·0170
		92		
3000	0·0360		3000	
		90		
3500	0·0450		and	0·0168
		78		
4000	0·0528		4000	
		62		
4500	0·0590		and	0·0127
		65		
5000	0·0655		5000	
		41		
5500	0·0696		and	0·0087
		46		
6000	0·0742		6000	
		50		
6500	0·0792		and	0·0098
		48		
7000	0·0840		7000	
		60		
7500	0·0900		and	0·0122
		62		
8000	0·0962		8000	

The striking distance for 8000 is 13·94 times that for 1000.

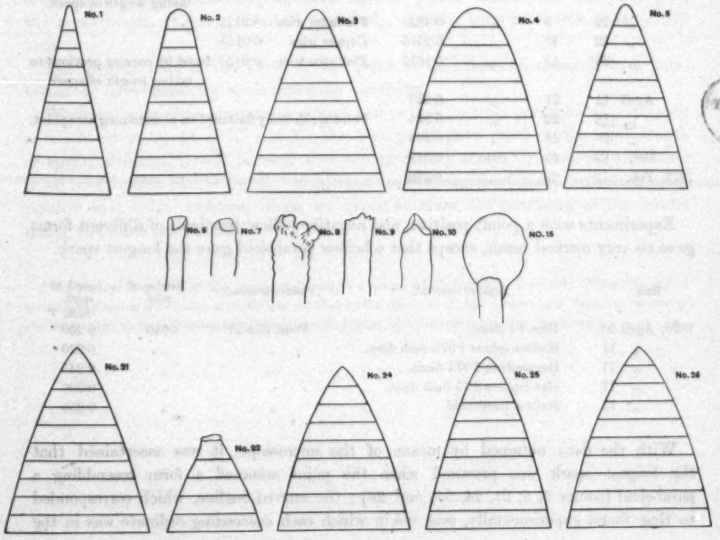
We now give some numbers to show that the striking distance between a point and a disc is remarkably constant for the same number of cells, provided that attention is paid to the shape of the point, for we have found by numerous experiments that much depends on its actual outline; for example, a conical point of 20° angle gives a spark of considerably less length than one of the same base and altitude, but paraboloidal in form; thus, when the point is positive, with 5640 cells, the ratio of the striking distance when the conical point is employed to that of a paraboloidal point is as 0·7764, and with 8040 cells as 0·7784 to 1.

With high tensions, 5000 to 8000 cells, the spark is longest when the point is positive, but with low tensions up to 3000 cells it is generally longest when the point is negative, as will be seen from the following numbers :—

Number of cells. (col. 1).	Length of spark. Point + (col. 2). inch.	Point − (col. 3). inch.	Ratio of col. 2 to col. 3.	Remarks.
8040	0·3430	0·1900	1·8	Mean of three observations made on different days.
5640	0·2230	0·1280	1·7	March 4, 1876.
,,	0·2420	0·1320	1·8	Feb. 15, 1876. A different point used.
3240	0·0600	0·0600	1·0	Feb. 12, 1876. A point of 20° used.
2160	0·0285	0·0400	0·71	Jan. 21, 1876. ,,
1080	0·0034	0·0050	0·67	Jan. 12, 1876. Battery No. 1 (powder) used.
,,	0·0037	0·0055	0·67	,, No. 2 ,, ,,
,,	0·0030	0·0057	0·67	,, No. 3 ,, ,,
,,	0·0070	0·0107	0·67	,, No. 5 (rod) ,,

In order to arrive at the best form of the point we took a wire of copper, brass, silver, platinum, zinc, magnesium, or steel, and turned it in a lathe to various outlines, making slight alterations as to sharpness, bluntness, or curvature between successive trials of the length of spark, and when a distinct result was obtained the

Fig. 12.



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point was placed under a microscope, and drawn by means of the camera lucida, a scale of $\frac{1}{100}$ths of an inch being subsequently drawn by means of the camera with the same magnifying power, and used for laying down co-ordinates for studying the shape of the point.

Fig. 12 represents some of these drawings reduced to half size, the spaces between the parallel co-ordinates being $\frac{1}{100}$ths of an inch; those figures without co-ordinates are drawn to the same scale.

The lengths of spark obtained with these terminals *positive* and a disc are as follow.—

Date.	No. of point.	No. of cells.	Length of spark. inch.		Diam. inch.	
1876. March 18	1	5640	0·173			
„ 17	2	„	0·200			
„ 17	3	„	0·243			
„ 18	4	„	0·125			
„ 21	5	„	0·230			
„ 22	6	„	0·162	Platinum wire	0·009	
„ 22	7	„	0·215	„	0·0125	
„ 22	8	„	0·198	Aluminium wire	0·015	fused by current previous to taking length of spark.
„ 22	9	„	0·182	Platinum wire	0·0125	
„ 22	10	„	0·2105	Copper wire	0·0155	
„ 23	15	„	0·1615	Platinum wire	0·0125	fused by current previous to taking length of spark.
April 11	21	„	0·229			
„ 16	22	„	0·216	Point accidentally flattened on ascertaining zero point.		
„ 20	24	„	0·244			
Oct. 19	25	8040	0·345			
1877. Feb. 13	26	„	0·342			

Experiments with a point, positive, and negative hollow terminals of different forms gave no very marked result, except that a hollow paraboloid gave the longest spark.

Date.	Negative terminal.	Positive terminal.	Number of cells.	Length of spark. inch.
1876. April 10	Disc 1·1 diam.	Point like 21	5640	0·239
„ 11	Hollow sphere 1·375 inch diam.	„	„	0·220
„ 11	Hemisphere 1·375 diam. . . .	„	„	0·245
„ 11	Hemisphere 0·95 inch diam. .	„	„	0·230
„ 11	Hollow paraboloid	„	„	0·255

With the data obtained by means of the microscope, it was ascertained that the longest spark was procured when the point assumed a form resembling a paraboloid (points 3, 5, 21, 24, 25, and 26); the curved outline, which corresponded to that found experimentally, was one in which each succeeding ordinate was in the

ratio of the square root of the odd numbers 1, 3, 5, &c., the sectional areas being consequently in the ratio of the odd numbers. The first ordinate was taken as 1·33 to the first abscissa 1. A diagram was laid down with 120 such ordinates to a scale of four feet for the length of the point, and then reduced by successive steps with a pantagraph to the size shown in fig. 13, X, this, with a certain modification,* served as a guide for a cutting-pantagraph to shape a cutting tool to be used in a lathe for forming the point of the size Y, fig. 13, to be actually used as

Fig. 13.

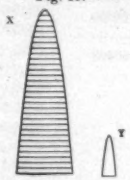
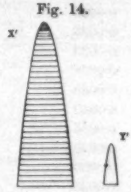


Fig. 14.



a terminal. Experiment proved that all the points made with this tool gave the mean length of spark obtained previously, namely, with 8040 cells, 0·340–0·350 inch.

The greater part of the curve of the point so laid down corresponds to a paraboloid or more correctly to intersecting parabolas.

We were induced to construct a second tool to make a truly paraboloidal point such as is shown in fig. 14 at X′ and Y′; this new point gave precisely the same length of spark, although it will be seen that the extremity of it (X′) does not terminate in an actual point like in fig. X. Subjoined are the lengths of spark between a point *positive* and a disc *negative*, which we quote to show the constancy of the results under the same conditions.

* As the guiding arm of the pantagraph carries a point which works in a groove, whilst the cutter to form the tool is a cylinder, a guide line parallel to the curve of X, but distant four times the radius of the cutter, has to be laid down to guide the tracing point, the reduction being to one-fourth.

FORM of terminals, a paraboloidal point + and a plate of 1·1 in. diameter —.

1080 CELLS.		1200 CELLS.		2160 CELLS.	
	inch.		inch.		inch.
1875. April 8	0·0038	1875. Dec. 20	0·00625	1875. June 29	0·02476
1876. Jan. 12	0·0034		0·00700	July 3	0·02400
	0·0038	1876. May 28	0·00625	Dec. 20	0·02000
	0·0030		0·00600	1876. Jan. 21	0·02850
Feb. 24	0·0033		0·00500	Feb. 24	0·02100
	0·0033		0·00600	Oct. 19	0·02000
	0·0033				0·02000
	0·0038	Mean	0·00608		0·02000
	0·0038				0·02000
Mar. 23	0·0040				0·02175
	0·0035				0·02250
	0·0040				
	0·0030			Mean	0·02204
	0·0035				
April 1	0·0035				
	0·0040				
	0·0040				
	0·0033				
May 10	0·0030				
	0·0030				
May 26	0·0030				
	0·0030				
June 7	0·0035				
	0·0035				
Oct. 19	0·0037				
Mean	0·0035				

2400 CELLS.

	inch.
1875. Dec. 18	0·0220
	0·0260
	0·0265
Dec. 20	0·0265
Dec. 30	0·0250
Dec. 31	0·0270
1876. May 28	0·0210
	0·0260
	0·0270
	0·0260
	0·0260
	0·0260
	0·0260
	0·0260
Mean	0·0255

3240 CELLS.

	inch.
1875. July 21	0·064
	0·058
Aug. 19	0·070
Nov. 5	0·054
	0·049
Nov. 8	0·055
Dec. 20	0·043
1876. Jan. 12	0·075
	0·106
	0·095
Feb. 24	0·075
	0·068
	0·068
April 1	0·062
May 26	0·042
Oct. 19	0·073
	0·073
	0·073
	0·074
	0·074
Oct. 23	0·063
	0·061
	0·061
	0·061
	0·061
Mean	0·067

3600 CELLS.

	inch.
1876. May 28	0·0845
	0·0855
	0·0855
	0·0855
Mean	0·0850

4320 CELLS.

	inch.
1876. Jan. 20	0·1290
	0·1320
Jan. 23	0·1525
Feb. 24	0·1240
	0·1230
April 1	0·1370
Oct. 19	0·1125
	0·1125
	0·1125
	0·1135
Mean	0·1258

5400 CELLS.

	inch.
1876. Feb. 24	0·2020
	0·2130
April 1	0·2225
Oct. 19	0·2040
	0·2040
	0·2050
Mean	0·2084

5640 CELLS.

Date.	Distance between terminals. inch.	Date.	Distance between terminals. inch.
1876. Feb. 15	0·2315	1876. April 17	0·2430
„ 15	0·2420	„ 20	0·2443
Mar. 4	0·2230	May 9	0·2400
„ 4	0·2400	„ 10	0·2340
„ 11	0·2420	„ 25	0·2320
„ 15	0·2410	„ 26	0·2380
„ 17	0·2430	„ 28	0·2280
„ 21	0·2400	„ 29	0·2350
„ 31	0·2430	„ 29	0·2200
April 1	0·2400		
		Mean =	0·2370

5640 CELLS.

Date.	Form of terminals.	Distance between terminals. inch.
1876. Jan. 10	A conical point of 20° + and plate of 1·1 in. diam. —	0·180
„ 11	„ „ „	0·174
Feb. 12	„ „ „	0·194
„ 13	„ „ „	0·212
„ 14	„ „ „	0·188
Mar. 15	„ „ „	0·175
	Mean =	0·184

Ratio of the striking distance with a conical and with a paraboloidal point =

$$\frac{184}{237} = 0{\cdot}7764.$$

8040 CELLS.

Form of terminals.

A paraboloidal point + and a plate from 1·1 in. to 1·5 in. diam. —

Date.	Distance between terminals. inch.	Date.	Distance between terminals. inch.	Date.	Distance between terminals. inch.
1876. May 28	0·341	1876. Aug. 12	0·348	1876 Dec. 5	0·355
„ 28	0·340	„ 15	0·352	„ 9	0·340
„ 29	0·340	„ 18	0·348	1877. Jan. 5	0·340
June 7	0·343	„ 19	0·343	Feb. 13	0·342
„ 8	0·340	Oct. 14	0·353	April 24	0·320
„ 10	0·335	„ 17	0·345	„ 24	0·340
„ 27	0·335	„ 19	0·345	May 7	0·340
July 10	0·340	„ 19	0·341	„ 15	0·344
„ 15	0·340	„ 21	0·341	„ 15	0·330
„ 19	0·344	„ 24	0·340	„ 18	0·348
„ 22	0·342	„ 25	0·340	„ 22	0·330
„ 25	0·340	Nov. 7	0·340	„ 23	0·340
„ 31	0·343	„ 27	0·355	„ 24	0·340
Aug. 4	0·340	„ 28	0·355	„ 28	0·350
„ 5	0·340	Dec. 1	0·355	„ 28	0·358
				Mean =	0·343

8040 CELLS.

Date.	Form of terminals.	Distance between terminals.
1877. May 24.	Conical point of 20° + and a plate 1·5 in. diam. —	·267

Ratio of the striking distance with a conical and with a paraboloidal point =

$$\frac{267}{343} = 0{\cdot}7784.$$

On Plate 8 we have laid down in curves the observations made on different occasions with a paraboloidal point and a disc from 1·1 inch to 1·5 inch in diameter, the point being uppermost, and made positive or negative; each particular case is distinguished in Table X. by the letters P and N, which always refer to the point, and denote that the spark was longest when so charged. Special experiments have shown that it makes no difference in the length of spark whether the point or disc is uppermost.

TABLE X., showing the lengths of spark in the curves of Plate 8.

Curve.	1080 cells. inch.	2160 cells. inch.	3240 cells. inch.	4320 cells. inch.	5400 cells. inch.	6480 cells. inch.	7560 cells. inch.	8040 cells. inch.	
XIII.	0·0055 N	0·0207 N	0·0734 N	0·1127 P	0·2043 P	0·2510 P	0·3150 P	0·3410 P	Oct. 19, 1876.
XVII.	0·0026 N	0·0165 N	0·0703 N	0·1260 P	0·2075 P	0·2280 P	..	..	Feb. 24, 1876.
XIX.	0·0102 N	0·0460 N	0·0750 N	0·1035 N	0·1650 N	..	..	..	Jan. 12, 1876.
XX.	0·0063 N	0·0400 N	0·0950 P	0·1525 P	0·1620 P	..	..	..	Jan. 23, 1876.
XXI.	0·0033 P	0·0285 P	0·1063 P	0·1305 P	..	..	..	..	Jan. 21, 1876.

MEAN of observations, pages 80 to 82.

Curve.	1080 cells. inch.	1200 cells. inch.	2160 cells. inch.	2400 cells. inch.	3240 cells. inch.	3600 cells. inch.	4320 cells. inch.	5400 cells. inch.	5640 cells. inch.	8040 cells inch.
XVI.	0·0035	0·00608	0·02204	0·0255	0·0670	0·085	0·1253	0·2084	0·237	0·343

SPECIAL observations.

Curve.	1200 cells. inch.	2400 cells. inch.	3600 cells. inch.	4800 cells. inch.	5640 cells. inch.	6840 cells. inch.	8040 cells. inch.	
XIV.	0·0058 N	0·0255 N	0·08525 P	0·1675 P	0·235 P	0·296 P	0·346 P	May 28, 1876.

Curve.	1200 cells. inch.	2400 cells. inch.	3600 cells. inch.	4800 cells. inch.	5880 cells. inch.	6960 cells. inch.	8040 cells. inch.	
XVIII.	0·00475 N	0·0200 N	0·0620 N	0·1520 P	0·2000 P	0·248 P	0·3400 P	June 26, 1877.

Curve.	600 rod cells. inch.	1200 rod cells. inch.	1800 rod cells. inch.	2400 rod cells. inch.	
XXIII.	0·00330 N	0·01300 N	0·0345 N	0·0535 N	Jan. 6, 1876.
XXIV.	0·00191 N	0·01075 N	0·0380 N	0·0565 N	Feb. 12, 1876.
XXV.	0·00205 N	0·01635 N	0·0415 N	0·0600 P	Feb. 12, 1876.
XXVI. Mean.	0·00242	0·01337	0·0380	0·0567	
XXVII. Theoretical.	0·003544	0·014176	0·03196	0·0567	

It is remarkable that the striking distances of 1080 and 2160 cells in curve XIX., and especially those of XXIII., XXIV., and XXV., obtained soon after two batteries each of 1200 rod cells were first charged up, in a single day, are much greater than

those observed with the same number of similar cells on subsequent occasions. Compare, for example—

	1200 cells.	2400 cells.
XIV.	0·0058	0·0255
XVIII.	0·00475	0·0200
with the mean of XXIII., XXIV., XXV.	0·01337	0·0567

By standing, as has been before stated, an oxychloride of zinc is formed on the surface of the zinc rods, and we have further noticed that the fluid in the cells becomes slightly alkaline; it is possible, but not certain, that the EMF may be diminished in consequence of the alkalinity, and the striking distance influenced by the change.* But, on the other hand, when a second series of 2400 cells was charged up, on May 27 and 28, 1876, no such unusual length of spark was obtained; hence we conclude that some special cause influenced the long discharge XXIII., XXIV., XXV., to be discovered by future experiment. A comparison of the numbers obtained when spherical or flat surfaces were used as terminals with those when a point and a disc or two points were used, will show that for low tensions the striking distance is fully as great, and in some cases greater, with spherical or flat terminals, than when one terminal was a point or when both were points.

From the curves laid down on Plate 8, which represents the original plotting reduced to $\frac{1}{4}$ths in each direction, we have deduced the numbers given in Table XI.

But, in the first instance, a mean curve was drawn for each of the irregular curves representing the actual observations; these mean curves are not given in Plate 8, in order to avoid confusion.

TABLE XI.—Showing the length of spark from the mean curves derived from those shown in Plate 8.

Curve.	1000 cells. inch.	2000 cells. inch.	3000 cells. inch.	4000 cells. inch.	5000 cells. inch.	6000 cells. inch.	7000 cells. inch.	8000 cells. inch.
XIII.	0·0057	0·0220	0·0540	0·100	0·160	0·220	0·283	0·347
XIV.	0·0050	0·0195	0·0550	0·110	0·173	0·236	0·298	0·358
XVI.	0·0030	0·0200	0·0567	0·108	0·169	0·233	0·299	0·366
XXVII.	0·0040	0·0160	0·0405	0·082	0·137	0·198	0·264	0·337
XXII. Mean of XIX., XX., XXI.	0·0080	0·0330	0·0710	0·114	0·158	..	..	..
XII. Mean	0·0051	0·0221	0·0554	0·103	0·159	0·222	0·286	0·352
XIIa. Theoretical	0·0055	0·0220	0·0495	0·088	0·1375	0·198	0·2695	0·352

* The batteries were on November 29th restored to their normal current-force by the addition of hydrochloric acid as described in the footnote to page 112, the cells then had an electro-motive force of 1·052 volt; before the addition of acid the fluid was slightly alkaline, and a cell was found to have an electro-motive force of 1·024 volt, which is not much less than that of the restored cell. Consequently the additional length of spark XXIII., XXIV., and XXV. cannot be accounted for by a greater electro-motive force at the time the experiment was made.—December 13, 1877.

TABLE XII.—Showing the results in volts.

Curve.	1000 volts. inch.	2000 volts. inch.	3000 volts. inch.	4000 volts. inch.	5000 volts. inch.	6000 volts. inch.	7000 volts. inch.	8000 volts. inch.
XII. Mean . .	0·0049	0·021	0·053	0·097	0·150	0·210	0·278	0·335
XIIa. Theoretical	0·0052	0·021	0·047	0·083	0·130	0·187	0·255	0·330

It will be seen from the above that curve XII., Plate 8, laid down from the means of all the observations, accords very closely with curve XII*a*, Plate 8, drawn on the hypothesis that the striking distance between a point and a plate is in the ratio of the square of the number of cells, as we stated to be the case in a previous communication.* It would, however, appear that there is a tendency in the curve to converge towards the theoretical curve as the battery is increased beyond a certain number of cells; and, therefore, it is possible that the law of the squares may not hold for very high numbers; at about 4000 to 5000 cells the curve diverges from the theoretical curve, but it approaches it again in the majority of cases beyond that number up to 8040 cells.

With two points the length of spark is greater for high potentials, 5400 to 8040 cells, than between a point and disc, but not for low potentials, as will be seen from the following numbers laid down in curve XV., plate 8:—

TABLE XIII.—Length of spark between two paraboloidal points.

Curve.	1080 cells. inch.	2160 cells. inch.	4320 cells. inch.	4320 cells. inch.	5400 cells. inch.	6480 cells. inch.	7560 cells. inch.	8040 cells. inch.
XV.	0·005	0·024	0·0614	0·1307	0·2287	0·2895	0·3620	0·401

By laying down a smooth curve, XVA, fig. 15, through the observed distances in curve XV., we have obtained the numbers given in Table XIIIA for multiples of 1000 cells; the second line shows the lengths of spark on the hypothesis of their being in the ratio of the squares of the number cells.

TABLE XIIIA.—Length of spark between two paraboloidal points.

Curve.	1000 cells. inch.	2000 cells. inch.	3000 cells. inch.	4000 cells. inch.	5000 cells. inch.	6000 cells. inch.	7000 cells. inch.	8000 cells. inch.
XVA.	0·005	0·021	0·053	0·110	0·178	0·249	0·324	0·401
Theoretical	0·0062	0·0251	0·0564	0·1002	0·1566	0·2255	0·307	0·401

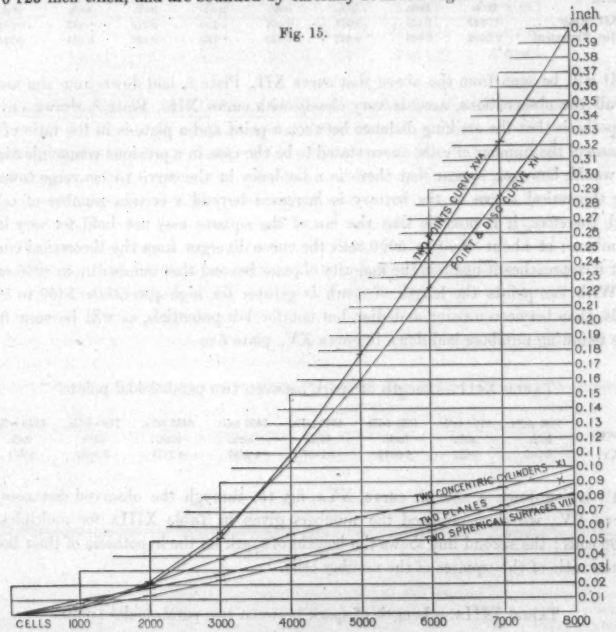
In order to show at a glance the relative striking distances between two spherical and two plane surfaces, two concentric cylinders, a point and a disc, and two points, we laid down on the same scale curves VIII., X., XI., XII., and XVA; the diagram, fig. 15, is a pantagraphic reduction of them to one third of the originals.

We may, however, state that we place greater reliance on the measurements of the length of spark up to that for 2000 cells between spherical surfaces than between

* Proc. Roy. Soc., vol. xxiv. p. 168.

planes; for not only is it difficult to keep the latter absolutely parallel, but also there is a tendency to discharge near the peripheries of the discs, notwithstanding that they are 0·125 inch thick, and are bounded by carefully rounded edges.

Fig. 15.



By connecting the battery with a condenser a much more dense spark passes, giving rise to a greater or less explosion as the capacity of the condenser is greater or less. The length of the spark is not affected in the case of spherical terminals being used, but is considerably shortened in that of a point and plate: thus with 8040 cells—

	Without condenser. Length of spark. inch.	With condenser. Length of spark. inch.
Two spherical surfaces 1·5 inch diameter and 8 inches radius	0·082	0·082
Point positive and disc negative	0·340	0·268

The condenser E, page 99, used in the above experiment, has a capacity of 0·148 microfarad.

With a Muirhead condenser of 13 microfarads' capacity, the 8040 cells gave a spark of 0·265 inch between a blunt point, positive (it is impossible to retain a good point with such heavy discharges, as metal is carried off at each explosion), and a flat surface 0·125 inch diameter, negative.

The actual jump of the spark when a point and disc or two points are employed as terminals is preceded by a luminous discharge (streamers), presenting phenomena of an interesting character, an extremely minute quantity of electricity passing as compared to that when the spark jumps and forms the arc, but still it is sufficient when caused to pass through a vacuum tube to illuminate it strongly.*

In illustration of this we quote the following numbers based on the statement before made, namely, that the electro-motive force of the battery per cell is taken at 1·03 volt, and the internal resistance at $4800 \times 5 + 3240 \times 15 = 72{,}600$ ohms.

	Weber.
8040 cells in short circuit would give a current of	0·1140
8040 cells, after the jump at 0·34 inch and the formation of the arc, the external resistance having been found to be 58,000 ohms	0·0634
8040 cells, at 0·36 inch between the terminals, the measured resistance being 327 megohms, with the point positive	0·0000247
8040 cells, at 0·36 inch between the terminals, the resistance being 274 megohms, with the point negative	0·0000302
8040 cells, at 0·30 inch between the terminals, the resistance 181 megohms, with the point negative	0·0000458
8040 cells, distance 1·16 inch, resistance 5890. megohms, the point positive or negative	0·0000014

Taking for unit the current which passes with no external resistance, that when the spark has jumped and the arc is formed is 51 per cent.; at 0·36 inch distance, 0·0217 per cent. $= \frac{1}{4600}$th; at 1·16 inch, 0·00123 per cent. $= \frac{1}{81300}$th. Taking for unit the current which passes when the arc is formed, the streamers at 0·36 inch give a current of 0·039 per cent., or $\frac{1}{2564}$th part of it.

Many determinations were made of the current passing between a paraboloidal point and a disc at various other distances beyond the striking distance. In order to make these measurements, the point was connected with one terminal of the battery, the other terminal being to earth; the opposed disc was connected to one terminal of a THOMSON galvanometer, whose constant had been accurately determined; the other terminal of the galvanometer was to earth. Every care was taken to prevent leakage, and the shunts were adjusted to suit the current. A danger to be guarded against was the jump of the spark, as the current which would then pass would injure the galvanometer.

From the above figures it will be seen that the streamer-discharge from a paraboloidal

* Proc. Roy. Soc., vol. xxiv. p. 169, 1876.

point at 0·36 inch distance from a plate diminishes the potential of the battery of 8040 cells by only $\frac{1}{4000}$th part, or less than two cells.

This discharge from the point when positive has mainly to the naked eye a stream-like appearance, consisting of a waving line of light surrounded by a very faint sugar-loaf luminosity and producing a rattling or strong hissing sound; from the point when negative it consists of a glow of light paraboloidal in form and extending from the point to the disc, but much more brilliant at the point, the noise of the discharge being much less than when the point is positive. The disc, especially when positive, soon becomes covered with a peach-like bloom, and the deposit assumes the appearance of NEWTON'S rings.

Small as this current is, it is, nevertheless, very manifest from its brightness and the rattling or loud hissing noise it produces; it frequently continues for some minutes before the spark actually jumps between terminals placed at the striking distance asunder; the streamer-discharge becomes brighter just before the jump and formation of the arc, and this suggested the possibility of particles being carried off in increasing quantity from the point to the disc, and thus contributing to the production of the spark. In order to test this hypothesis, the terminals were placed at the striking distance and a continuous blast from a blowpipe bellows sent between them;

Fig. 16.

this did not, however, have any effect on the length of the spark, but it deflected the arc when once it had formed.

Under the microscope the discharge, from the point when positive, is seen to consist of several streams of light, which twist round each other like loosely-bound strands, as shown in fig. 16, representing the discharge between the terminals in a horizontal discharger. Part of the discharge from the point negative is shown in fig. 17.

In order to study these discharges, we had constructed for us a microscope (fig. 18) with a revolving mirror placed at an angle formed by the two tubes composing the

body of the microscope, which is bent for the convenience of observation. That part beyond the upright is formed of ebonite, in order to protect the eye from accidental shocks. The discharger used when this microscope is employed is

Fig. 17.

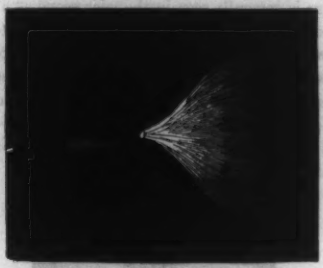
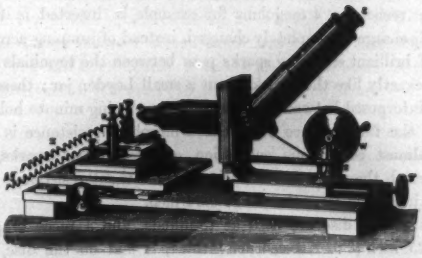


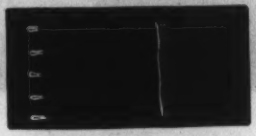
Fig. 18.



horizontal, as seen in the figure, in order to permit of the employment of the mirror which is mounted on a horizontal axis; the point P is placed in the fixed upright, and the disc D in that upright which is attached to the adjustable slide. The screw S′ is used to approach or recede the microscope in order to adjust to focus; S″ to bring the point horizontally, and S to elevate or depress the microscope by means of a pinion and rack to adjust the point vertically in the field. O is the object-glass and E the eye-piece; W, a multiplying-wheel giving five revolutions of the mirror for one turn of the handle, which may be rotated with ease 200 times in a minute, so that the mirror can be caused to make 1000 revolutions in a minute, or about 17 revolutions in a second. The whole framework of the stand is of ebonite to ensure insulation.

When the revolving mirror is set in motion it is seen that the streamer-discharge is in reality to a great extent intermittent. At times a moderate rotation-velocity of the mirror serves to show this by the production of a number of distinct images, as seen in the left-hand drawing in fig. 19; at others it requires the full speed of the mirror. The discharge appears much more continuous with the point negative, so much so that the image is generally seen in the microscope as a sheet of light brightest near the point, and nearly uniform in a direction at right angles to the axis of the mirror; the right hand drawing shows the appearance when the point is negative. The difference in the sound emitted when the point is positive and negative respectively appears to afford an additional proof of less continuity in the case of the positive, see also page 118.

Fig 19.



When a high resistance, 4 megohms for example, is inserted in the circuit, the character of the discharge is completely changed, instead of jumping across and forming an arc, a series of brilliant snapping sparks pass between the terminals at more or less rapid intervals, exactly like the sparks from a small Leyden jar; these pierce a piece of writing paper interposed between the terminals producing minute holes. The spark does not jump at the full distance when the 4 megohms' resistance is inserted; and, to produce an almost continuous succession of intermittent sparks, it is usually necessary to approach the point to 0·30 inch, when, without resistance, the spark with 8040 cells would jump and form the arc at 0·34 inch.

When a point and a disc are used as terminals, and a piece of glazed writing paper, say 0·00425 inch (0·01079 centims.) thick, is laid on the disc, a very strong adhesion of the paper to the disc takes place, and it requires a strong pull to draw it along; this phenomenon was first noticed by our assistant, Mr. FRAM. In order to measure this force of adhesion we used a spring dynamometer, with a clip to hold the strip of paper, 1½ inch wide (the width of the disc). Under ordinary states of moisture of the atmosphere, with 8040 cells it required a pull—

When the point was positive.	When it was negative.
grains.	grains.
of 1300	of 2900
1300	2800
1100	3200
Mean 1233	Mean 2933

to draw the paper along the disc, presenting a surface of 1·767 square inch (11·401 square centims.) a flat plate laid on the paper required to be loaded, in order to indicate the respective pulls, to 5,200 grains when the point was positive, and 8,900 grains when negative. This strong adhesion arose evidently from the charging up of the upper surface of the paper with the opposite electricity to that of the disc, and hence it appeared probable that by making the paper thoroughly dry the upper surface ought to take a higher charge and cause a stronger adhesion, and this was found to be the case.

In order to measure the force of adhesion when the paper was well dried, we had successively made two new dynamometers, as the first only ranged to 4000 grains; the pull so much exceeded our anticipations, that the second—from 3000 to 10,000 grains—was found to be insufficient. Ultimately, one ranging from 10,000 to 50,000 grains was employed. The strain required to pull away the paper was—

With the point negative, 30,000 grains.
" positive, 18,000 "

These strains were reproduced when the paper was under the pressure of 129,690 grains (8403·8 grms.) and 53,530 grains (3468·6 grms.) respectively. On the hypothesis of two parallel plates (the upper surface of the paper and the disc-terminal) each of area (A) = 11·401 square centims., at a distance (D) = 0·01079 centim., the thickness of the paper, between which there is a force of attraction (F) = (gW) = 8403·8 grms. × 981 and 3468·6 grms. × 981 in the several cases, we have the following values for the difference of potential (V) between the two planes:—

$$F = g\,W = A\frac{V^2}{8\,\pi\,D^2}$$

$$\text{whence, } V = D\sqrt{\frac{8\,\pi\,g\,W}{A}}$$

or, when the point was negative—

$$V = 0{\cdot}01079\sqrt{\frac{8 \times 3{\cdot}14159 \times 981 \times 8403{\cdot}8}{11{\cdot}401}} = 46{\cdot}0205 \text{ electro-static units.}$$

$$= 46{\cdot}0205 \times \frac{3 \times 10^{10}}{10^8} = 13{,}806{\cdot}15 \text{ volts.}$$

and, when the point was positive—

$$V = 0{\cdot}01079\sqrt{\frac{8 \times 3{\cdot}14159 \times 981 \times 3468{\cdot}6}{11{\cdot}401}} = 29{\cdot}5563 \text{ electro-static units.}$$

$$= 29{\cdot}5663 \times \frac{3 \times 10^{10}}{10^8} = 8869{\cdot}89 \text{ volts.}$$

The value obtained for the point positive does not differ very greatly from the number of volts (8281) actually employed; but that for the point negative is in the ratio of 1·67 to 1.

In calculating the force of attraction, it has been assumed that it was the upper surface of the paper which was charged to the highest negative or positive potential, according as the point was negative or positive, but it is possible that a zone of almost full potential was at some nearer distance from the metallic disc. It has been suggested that the whole mass of the paper serves as a conductor, resting on only a few points on the lower disc, and that the intervening film of air is the insulator; against the correctness of this hypothesis is the fact that the adhesion is much stronger when the paper is made to insulate better by being dried. With paraffined paper black-leaded on the upper surface the adhesion was with point N 900 and with point P 400 grains, and it was almost inappreciable when the upper surface of the slip of paper had a disc of tin-foil pasted on it.

There is no measurable adhesion when a spherical surface is substituted for the point: this was to be expected, for there is scarcely a visible glow, and consequently little transference of electricity before the jump of the spark. The only effect observed was that the slip of paper was attracted diagonally to both terminals, forming a bridge through which a minute current passed when the terminals were separated beyond the striking distance.*

When one of the terminals consists of a very fine platinum wire 0·002 inch diameter, and about 0·56 inch long, held in a holder like that used for holding needles in a mathematical instrument box, but adapted to go into our discharger, the wire takes up a straight, circular, or elliptical oscillation, the glow at the point forming a continuous line of light marking its course; with the point positive the excursion is less than when negative, being with a potential of 8040 cells, and a distance between the terminals of 0·32 inch, about 0·375 inch, while with the point negative it is much more brilliant and about 0·8 inch. By interposing a resistance of 4 megohms the statical discharge takes place from the extremity of the wire, frequently producing a beautiful and brilliant figure by the apparent crossing and interlacing of the bright lines of discharge from different points in the path of the oscillating wire; these occur at such short intervals that the discharge looks like a persistent pattern of intricate engine-turning. By approaching the wire cautiously it is generally possible to cause the end of it to fuse into a minute globule, and the discharge then becomes much more striking. With 4 megohms' resistance the static spark is longest and brightest when the wire is negative; if the wire is very straight the oscillations take place in a cycloidal curve in a vertical plane, the discharge occurring at equal distances from the middle of the path as the minute globule at the end of the wire attains the limit of the greatest discharge from either side, so that two streaks of light are seen continuously; if the wire is slightly

* Professor STOKES, to whom we communicated these results, has favoured us with some remarks, which we insert with his permission in Note A.

bent the oscillation is conical or elliptical, and the figure produced by the discharge is then much more continuous and beautiful, because the distance from the point to the plate remains nearly constant. The difference of the amount of excursion of the wire when positive or negative is one of the many instances of the difference of the positive and negative electric force.

In the foregoing account of the length of the spark no mention has been made of the atmospheric conditions in relation to pressure, temperature, or hygrometric state, because it was found that it was not affected thereby to any appreciable amount, the laboratory being warmed during the cold period; but it is nevertheless certain that some effect must be produced by variations in temperature, as it was found that a very high temperature, such for example as that produced by the flame of an insulated spirit lamp, caused a much greater jump between the terminals, for instance, with 8040 cells, the length of spark between a point and a ball 1 inch in diameter was 1 inch, and between two points 1·375 inch; the length of the spark is somewhat influenced by the position of the flame, and is greatest towards the point or oxidising part of it.

When the terminals are placed opposite to two gas jets emanating from the same gas pipe in metallic communication with the gas main, and consequently to Earth, the flame opposed to the negative terminal is attracted, and that opposed to the positive repelled, as was observed to be the case with static electricity by M. Neyreneuf,* at whose request we have made the experiment. Fig. 20 shows the arrangement and effects observed.

Fig. 20.

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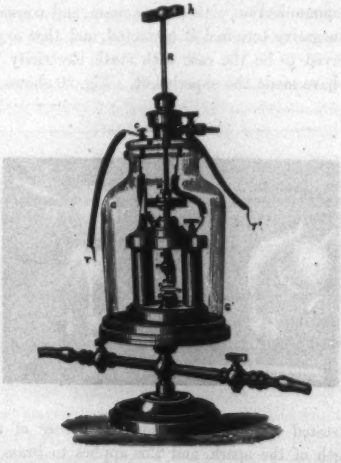
We have already stated that in most cases the nature of the metal makes no difference in the length of the spark, and this applies to brass, copper, silver, steel, platinum, magnesium, and zinc; but there is a striking exception, namely, aluminium, which gives a considerably longer spark when used for a terminal in the shape of a point; thus, when the point was positive, with—

* Annales de Chemie et de Physique, 5e serie, t. ii. 1874.

Date.	Cells.	Copper point + Length of spark. inch.	Aluminium point + Length of spark. inch.	Ratio of spark with aluminium to that with copper =
1876. March 21 and 22	5640	0·240	0·320	1·300
1877. July 9 . . .	8040	0·340	0·411	1·209
„ 10 . . .	„	0·340	0·414	1·217
			Mean	1·242

The length of the spark differs in various gases at ordinary atmospheric pressures, as we anticipated that it would do from our experience with vacuum tubes; but the difference in the length of the spark does not bear any precise ratio either to the specific gravity of the gas or its viscosity in reference to mechanical impulse; we therefore propose to ascribe it, at all events provisionally, to a difference of *electric viscosity*. In order to make experiments on the discharge in different gases, we placed the discharger, already described page 58, fig. 1, under a bell glass G G′ (fig. 21), open at the top and covered with a glass plate, P.

Fig. 21.



The glass plate has two screw-clamps, which are connected at its under surface with wires led from the screw-clamps c and c' (fig. 21) of the discharger. In connexion with these, on the outside surface, are two other screw-clamps c c′ with which the terminals of the battery T T′ are connected. Through a stuffing box in the glass cover a

steel rod R passes; this, below the glass, carries a crutch M, with two ebonite pins, which drop into corresponding holes made to receive them in the micrometer wheel A, fig. 21; the rod has on the top, outside the jar, a cross handle *h* of ebonite for turning it. The distance of the terminals is easily regulated by means of this rod, as the micrometer can be read through the bell glass. Before admitting any gas into it, the bell glass was exhausted by the mercurial pump to a pressure of less than a millimetre, then filled with dry gas, and again exhausted and recharged. The following Tables XIV. and XV. show the results obtained both with spherical surfaces 1·5 inch in diameter and 3 inches radius, and also with paraboloidal point and a disc 1·5 inch diameter.

TABLE XIV.—Striking distance between two spherical surfaces with 8040 cells.

Gas.	Striking distance.	Ratio of striking distance.		Ratio of electric viscosity.	
		Referred to air.	Referred to hydrogen.	Referred to air.	Referred to hydrogen.
	inch.				
Air	0·082	1·000	0·547	1·0000	1·828
Hydrogen . . .	0·150	1·829	1·000	0·5467	1·000
Oxygen	0·082	1·000	0·547	1·0000	1·828
Carbonic anhydride	0·077	0·939	0·513	1·0650	1·949

TABLE XV.—Striking distance between a point + and disc — with 8040 cells.

Gas.	Striking distance.	Mean ratio of striking distance.		Electric viscosity.	
		Referred to air.	Referred to hydrogen.	Ratio to air.	Ratio to hydrogen.
	inch.				
Air	0·344	1·000	0·5783	1·000	1·745
	0·300				
Hydrogen . . .	0·600	1·808	1·0000	0·553	1·000
	0·562				
Nitrogen	0·402 (air 0·300)	1·340	0·7153	0·746	1·399
Oxygen	0·212				
	0·220	0·674	0·3718	1·484	2·689
Carbonic anhydride	0·120				
	0·160	0·441	0·2409	2·268	4·149

When charcoal terminals are used the jump of the spark is about the same as with other terminals having a similar shape; the charcoal points may be separated when 8040 cells are used to 1·25 inch generally, and occasionally to 1·5 inch without breaking the arc. If the current were greater, as would be the case with larger cells, the arc would no doubt be much longer. The arc presents the ordinary characters, as shown in fig. 22; but that which takes place when the terminals are vertically one over the other, as in our discharger, is different, on account of its being undisturbed by upward air currents which deflect the arc.

The appearance of the arc is different in different gases, as will be seen in fig. 23, where 1 represents the arc in air; this when examined with the microscope presents an evidently stratified appearance, especially in the barrel-shaped surrounding of the central bright spindle; the laminæ are extremely close, and seen with very great

difficulty, even with the revolving mirror of the microscope, which must be caused to revolve at different velocities to render them apparent; with a moderate magnifier, a hand lens, the barrel-shaped surrounding appears as if shaded with lines across it. As one examines the arc with the mirror revolving at a great velocity, evidence of the carrying of minute particles is given by streaks of bright light, which cross the field.

The arc in hydrogen, with the point positive, is shown in 2, fig. 23; the central spindle is surrounded by a beautiful blue halo, like a glass shade illumined by

Fig. 22.

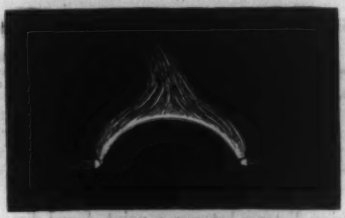


Fig. 23.

fluorescent light, and very brilliant on the disc; with 8040 cells the spark jumped on one occasion 0·562 inch when the point was positive, and only 0·462 inch when negative; the ratio of negative to positive 1 = 0·822. With 4 megohms' resistance in the circuit, the streaming discharge from the point positive, at 0·502 inch distance, was carmine in colour. This distinctive colour is a proof that the gas in which the discharge takes place is the carrier of electrification in the streamer discharge. The appearance of the arc when the point is negative is shown in 4; it moves about very

rapidly, and forms a star-like appearance on the positive disc; when the point is negative, before the jump of the spark, a very pale glass-shade-like halo, of a saddened olive tint, extends from the point almost to the outer periphery of the disc.

The arc in nitrogen is reddish-violet, the jump with 8040 cells being 0·402 inch when the point is positive, and 0·272 inch when negative, or in the ratio of negative to positive of 0·677.

In oxygen the arc presents a similar appearance to that in air, the mean jump with 8040 cells being 0·216 inch with the point positive, and the mean when negative 0·137 inch, the ratio of negative to positive being 0·634 to 1. The arc in carbonic anhydride is shown in 3, fig. 23.

From the foregoing observations, it would appear that hydrogen in a residual vacuum, together with the employment of aluminium for terminals, present the most favourable conditions for the passage of the voltaic current.

The spark with 8040 cells jumped 0·5 inch between two points placed vertically one over the other in a tube containing absolute alcohol, and provided with a vent to permit of the alcohol vapour escaping as soon as the arc is formed. Dr. BLEEKRODE, it

Fig. 24.

will be remembered, communicated to the Royal Society a paper 'On Electrical Conductivity and Electrolysis in Chemical Compounds,'* in which he gave an account of some experiments performed in our laboratory; as we do not propose to enter into this subject already in the skilful hands of that able chemist and physicist,

* Proc. Roy. Soc., No. 175, 1876.

we merely recall what has been stated by Dr. BLEEKRODE, that fluids such as bisulphide of carbon (CS_2), benzine ($C_6 H_6$), tin tetrachloride ($SnCl_4$), hydrochloric acid (HCl), cyanogen ($C_2 N_2$), zinc ethyl ($Zn (C_2 H_5)2$), are all strongly agitated when the current passes, but there is no electrolytic decomposition. The fluid is repelled by the negative and attracted by the positive pole, as shown in fig. 24, giving proof of a molecular motion taking place during the passage of the current, this has been found to occur even when the current passes slowly from one plate of a condenser to the other. We cannot, however, refrain from observing in reference of Dr. BLEEKRODE's experiments, that it is most remarkable that fused chloride of lithium (LiCl) is readily decomposed by four BUNSEN cells, and fluid hydrochloric acid (HCl) resists a potential of 5640 cells; the accepted notions of electrolysis evidently requiring reconsideration.

Battery in combination with an Accumulator (condenser).

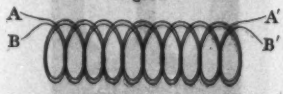
For several experiments we employ the accumulated charge of a condenser, and have condensers of different constructions and capacities, thus :—

1st. Two globes, covered with tinfoil and then with india-rubber, to prevent the dispersion of the charge ; the axis is supported on ebonite uprights attached to a wooden base. The globes are 18 inches (45·72 centim.) in diameter, and present each a superficies of 7·07 square feet (65·68 square decim.) ; the capacity of each = 0·00037 microfarad.

2nd. Two cylinders, made of many folds of paper, covered with tinfoil and then with several other layers of paper ; they are supported on three ebonite feet. Each cylinder has a superficies of 16 square feet (148·64 square decim.) ; these have each a capacity of 0·00052 microfarad.

3rd. Coil condensers, composed of two insulated copper wires coiled together side by side on a reel, shown in the diagram (fig. 25) :—

Fig. 25.



Coil A consists of two wires, 174 yards (159 metres) long, and $\frac{1}{16}$ of an inch (0·16 centim.) diameter ; these wires are covered with gutta-percha in two layers, being together $\frac{3}{32}$nd of an inch (0·08 centim.) thick ; this has a capacity of 0·014 m.f.

B. A similar coil, 350 yards (320 metres) long, with a capacity of 0·031 m.f.

C. A coil of the same thickness and length of wire, 350 yards, covered with india-rubber and linen, $\frac{8}{32}$nds of an inch (0·24 centim.) thick = 0·028 m.f. This coil supports a charge of 3600 cells, A and B only 2400.

4th. Plate condensers :—

D. Four condensers, formed of sheets of tinfoil and sheets of ebonite $\frac{1}{32}$nd of an inch (0·08 centim.) thick ; these each are in four sections :—

	Square feet.	Square decim.	Microfarad.	
D 1	29	269·5	0·0924	These support a charge of 3600 cells, but are liable to break down with 4800.
D 2	145	1347	0·4518	
D 3	145	1347	0·4704	
D 4	145	1347	0·4741	

E. Composed of tinfoil, separated by two sheets of vulcanized rubber, each $\frac{1}{32}$nd of an inch thick ; it is in four sections and has a total surface of 75 square feet (698 square decim.), and a capacity of 0·1485 m.f. ; this bears a charge of 8040 cells.

F. A condenser, composed of tinfoil and paraffined paper, in eight sections ; it has a total capacity of 42·8 * m.f., and was made for us by Messrs. VARLEY ; it is capable of withstanding a charge with 3240 cells.

G. A similar condenser, made under the direction of Dr. MUIRHEAD, of 240 sheets of tinfoil, with seven sheets of paraffined paper interposed ; this presents a surface of 364·5 square feet (3386 square decims.), and has a capacity of 3·94 microfarads ; it bears a charge of 8040 cells.

H. Another, made under the direction of Dr. MUIRHEAD, with eight sheets of paraffined paper between the layers of tinfoil ; the surface of this is 2200 square feet (204·38 metres), and the capacity 20 microfarads.

5th. We sometimes employ Leyden jars of the following dimensions :—

	Square inches.	Square decim.	Microfarad.
H 1	57	3·68	0·0016
H 2	258	16·64	0·0049
H 3	442	28·51	0·0066

We give the foregoing particulars as affording useful information to other experimenters who may have occasion to employ accumulators. The coil condensers we have found useful in certain cases, as for example those already communicated to the Royal Society.† The VARLEY condenser is of very great value for experiments with vacuum tubes, for when once charged up, and then disconnected from the battery, and the charge allowed to run down through a tube, it maintains a current frequently for ten minutes without replenishing, the phenomena varying as the potential falls ; when any particular phase in the stratification occurs, it may be sustained by connecting the condenser with the battery through a suitably-adjusted resistance, which permits of the inflow being exactly equal to the outflow. The potential at each end of the tube and at different points in the circuit may be ascertained for

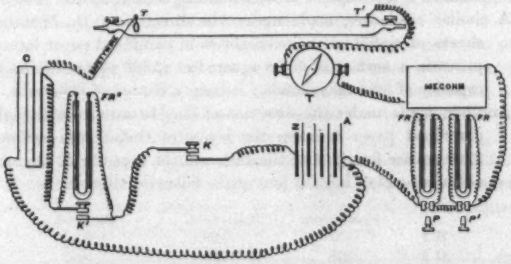
* The condenser of 47·5 m.f., described Proc. Roy. Soc., vol. xxiii. p. 358, broke down with 1080 cells.

† Proc. Roy. Soc., vol. xxiii. p. 356.

each phase by means of an electrometer; from these observations, data may be derived with respect to the current and the apparent resistance of the tube at each epoch. In using a condenser of this capacity certain precautions are necessary, for it several times has happened that there is no indication of a current until a sudden jump takes place which destroys the vacuum tube; this was remedied by placing a safety wire of platinum, 0·002 inch in diameter and 10 inches long, between the tube and one terminal of the condenser. Such a wire was found to permit of only 4 per cent. of the charge passing, and though frequently deflagrated by this amount of charge during the course of the experiments, it has effectually protected the tube by thus breaking off the connexion. We are indebted to our friend Professor STOKES for the suggestion of the introduction of resistances during the charging of the condenser and also for that of the safety wire.

Fig. 26 is a diagram of the arrangement. C, the condenser, one side of which is in

Fig. 26.



connection permanently with the battery at A, the other side is in connection with the battery at Z only when the key K (corresponding to K K′, fig. 9, page 63) is pressed down; this connection is either through the adjustable fluid resistance FR″ or direct, without intervening resistance, when the key K′ (corresponding to S S′, fig. 9) is pressed down; T T′ is the tube to be experimented with; the current from the condenser has to pass through the safety wire, the tube, and the adjustable coil resistance in the megohm, or the adjustable fluid resistances FR, FR″ [see also fig. 10, page 64], which may be plugged out by the plugs P and P′; or through both coil resistances and fluid resistance if so required. When K is raised, the charged condenser supplies the current.

We have already stated * that a charge of 47·5 microfarads, with 1080 cells, deflagrates 10·5 inches (26·67 centims.) of platinum wire, 0·005 inch (0·127 millim.) in diameter; when the condenser of 42·8 microfarads is charged up, with 3240 cells, the charge deflagrates the same length of wire, but 0·0125 inch (0·317 millim.) in diameter.

* Proc. Roy. Soc., vol. xxiii. p. 356.

The condenser of 42·8 is to that of 47·5 as 0·9434 to 1; the sectional area of the larger to the smaller wire is as 6·25 to 1; so that the effect of the disruptive discharge of 42·8 microfarads, with 3240 cells, as compared with that of 47·5 microfarads, with 1080 cells, is as 6·62 to 1 for the same capacity. As the relation of the electric energy in the two cases is that of the capacity multiplied by the square of the potential, the quantity of wire deflagrated should be $0{\cdot}9434 \times 3^2 = 8{\cdot}5$ to 1.

When 2½ inches of the same size wire, 0·0125 inch, of either platinum, gold, silver, copper, iron, zinc, or aluminium, is strained across and kept in close contact with a piece of plate glass, perforated with two holes to admit of screw clamps to press the ends of the wire tightly against it, and the charge sent through it, the wire is dispersed with a strong explosion, like that of a pistol, the metal being driven into and strongly adhering to the glass for some distance from the wire. The stain presents the appearance of lines of force, recalling magnetic lines, in consequence of the cloud or smoke-like stain being furrowed with lines converging towards the clamps. On examination with the microscope, it was seen that minute globules of metal existed at the termination of the furrows, which they had evidently ploughed up through the cloud-like deposit, leaving a line of unstained glass. Several of these globules, of gold, were measured under the microscope with a spider-line micrometer, and the following diameters were obtained among others:—0·00004, 0·00386, ·00463, 0·009 inch, they are all smaller than that of the wire exploded. The greater number were exceedingly minute, ending in a cloud-like stain too small to admit of measurement. All along the path of the discharge the deposit appears in cross striæ, which remain visible on the disintegrated surface of the glass when the film of metal is dissolved; the greatest dispersion is not close to the ends of the wire, but towards the middle, and was found to be—

With gold, 0·5.	With silver, 0·3.	With platinum, 0·3.
0·5.		„ 0·3.
0·55.		
0·6.		

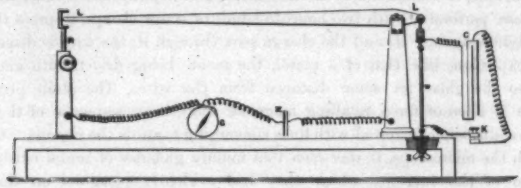
of the total length of the wire from the positive pole. The plate when gold has been deflagrated exhibits the metal in the several varieties of ruby, green, and violet.

The appearance of the stain of an exploded wire, suggested the thought of a stress at right angles to the path of the discharge; and experiments were made in order to ascertain whether a wire was either shortened in consequence of an expansion of its diameter, or lengthened by the particles being driven away from each other in the direction of its length by the discharge of 42·8 microfarads charged with 3240 cells, but the results were entirely negative. The diagram, fig. 27, shows the arrangement of the apparatus.

To the short end of a steel-yard L L′, whose relative lengths on each side of the

fulcrum are 1 and 13·6, was hung a brass wire W, 8 inches long and 0·2 inch diameter, by means of an insulated hook with a clamp for connexion with one plate of the condenser C. The wire was strained down in opposition to a small weight on the long arm of the steel-yard by means of the insulated screw-hook S connected with the contact-key K; when the charge is to be sent through the wire, this key has to be pressed down. To the metallic support of the lever is attached one terminal of a

Fig. 27.



single cell A Z, the other terminal being connected through a Thomson-galvanometer G to the adjustable metallic fork R. If contact between the long arm of the steel-yard and either the top or bottom of the fork takes place, then a current passes and the movement of the galvanometer indicates that the wire has either shortened or lengthened. When the long arm of the lever was adjusted to 0·001 inch from touching the top or the bottom of the fork, as the case might be, and the charge in the condenser was sent through the wire, contact was not made, showing that no shortening or lengthening to the extent of $\frac{1}{1360}$ inch occurred at the time of the discharge. When 8 inches of platinum wire, 0·0125 inch diameter, was experimented with, no instantaneous shortening of the wire took place at the moment of its deflagration. When 8 inches of iron wire, 0·03 inch diameter, was experimented with, a downward movement of the long arm of the lever to the extent of 0·375 inch occurred, showing an elongation by the heating effect of the discharge of $\frac{0{\cdot}375}{13{\cdot}6} =$ 0·02786 inch; the contraction of the wire in cooling brought the long arm of the lever to nearly, but not quite, its normal position; the elongation indicates a temperature of about 300° C., but it is most probable that it was higher, so that it may be safely concluded that the elongation of the wire was solely due to the heat.

We have made experiments to ascertain the amount in chemical equivalents required to fully charge the 42·8 microfarads accumulator by connecting a voltameter in the circuit to one of its plates, from one terminal of the battery, the other terminal to the other plate. The connexion in every case was continued for two minutes, although the evolution of the mixed gases in the voltameter had nearly ceased in thirty seconds; a very minute quantity, indeed, of gas continues to be liberated, however long the accumulator remains in connexion with the battery; this we attribute to a leakage.

In all cases either four or five charges were made, because the quantity of gas evolved is extremely small. The voltameter was specially constructed and subdivided, with a sufficient space between each division, to 0·02 of a cub. centim.

	Charge, with No. of cells.	Mixed gases evolved. cub. centim.	Temperature. Cent.	Barometer. millims.
I.	1080	0·0075	19·8	759·19
	2160	0·0150		
	3240	0·0250		
II.	1080	0·0100	20·8	756·14
	2160	0·0150		
	3240	0·0250		
III.	3240	0·0247	19·1	725·92
IV.	3240	0·0278	22·2	755·13

CHARGE with 3240 cells reduced to 760 millims. and 0° Cent.

	Mixed gases. cub. centim.
I.	0·02276
II.	0·02256
III.	0·02156
IV.	0·02487
Mean	0·02294

Taking 1000 cub. centims. at 760 millims. and 0° Cent. of mixed gases at 0·5365 grm., the charge is represented by—

$$\frac{0{\cdot}02294 \times 0{\cdot}5365}{1000} = 0{\cdot}000012307 \text{ grm. water decomposed,}$$

equivalent to 0·000166145 grm. silver reduced. A Weber of current flowing for one second would, according to KOHLRAUSCH (Pogg. Ann., vol. cxlix., 1873), reduce 0·0011363 grm. silver, and this being the quantity contained in a condenser of one farad when charged to a potential of 1 volt, we have—

$$\frac{0{\cdot}0011363 \times 42{\cdot}8 \times 3240 \times 1{\cdot}03}{1{,}000{,}000} = 0{\cdot}0001623 \text{ grm. silver,}$$

reduced by the charge of the 42·8 microfarads at the potential of 3240 AgCl cells. The ratio of the value observed by us (0·000166145 grm.) is to that calculated from KOHLRAUSCH'S numbers, as 102·3 to 100.

The *quantity* of electricity which flows into an accumulator to charge it fully, is in direct ratio of the number of cells; the potential also is proportional to the number of cells in series used to charge it, so that the electric energy is in the ratio of the capacity multiplied by the square of the potential.

Cells.	I. Ratio.	II. Ratio	Mean
1080	1·00	1·0	1·00
2160	2·00	1·5	1·75
3240	3·33	2·5	2·91

Taking experiment I., which was made with rod batteries which had been just previously tested, we have the ratios 1, 2, and 3·33 as the charges of the 42·8 microfarad condenser, with respectively 1080, 2160 and 3240 cells. We might, therefore, anticipate that the effects in deflagrating a wire would be as 1, 4, and 10.

A direct experiment with platinum wire 0·0125 inch diameter gave the following results, the charge with—

Cells.		Inches.	
1080	heated	1	to the fusing point.
2160	deflagrated	4	
	heated	5	to the fusing point.
3240	deflagrated	10·5	
	melted	11	into globules.
	heated	13	to the fusing point.

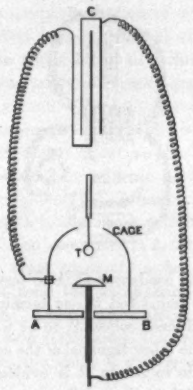
As occasionally we have accidentally been exposed to shocks, it appeared to us permissible, in self-protection, to ascertain whether life or health was in any way endangered by them; we therefore made an experiment on a rabbit, with the condenser of 42 8 microfarads charged with 2160 cells; the discharge was passed from the inside of one ear to the throat, but produced no other effect than to paralyze the fore paws for about an hour; it appeared, however, that but a very small portion of the charge had passed through the rabbit, inasmuch as afterwards, when the condenser was discharged, the report was nearly as loud as when the condenser is at full potential. Professor STOKES accidentally received the charge of this condenser, with 3240 cells, without injury (like the rabbit, he got only a small fraction of the charge), and one of us (DE LA RUE) has had a shock from the whole battery, without a condenser, of 8040 cells; the shock was severe, and its numbing effects were felt for some hours; in every case the skin is pierced by a number of minute holes and cauterised where the charge enters.

Experiments were made to test the portion of a charge that passed from a condenser when the opposite plates were connected by a certain length of platinum wire of a definite diameter. In order to measure the fall in potential of the condenser, one of its plates is placed in connexion with the cage (fig. 28), consisting of a glass shade lined with tinfoil, and having a hole in the top to permit of the insertion of a test plane, T, for taking a charge from the mushroom, M, in connexion with the other plate of the condenser, C. The shade rests on a glass disc, also coated with tinfoil, except at the centre, where a space 3 inches in diameter is left uncoated. For the suggestion of this arrangement, having for its object to insure that the test charge shall be always at the full potential, we are indebted to Professor STOKES. The cage is quite close to the quadrant electrometer, which we charge always to the potential of 2400 cells; it is rendered much less sensitive than usual by the separation of the suspension threads. The test plane we use up to 3240 cells is a brass disc 2 inches in diameter.*

* Recently we have found it to be more convenient to use a quadrant electrometer furnished with an induction plate placed above one of the quadrants and adjustable in distance from it.—Dec. 13, 1877.

42·8 microfarads were charged with 2160 cells, and gradually discharged by connecting the opposite plates many times in succession through a platinum wire of 0·002 inch diameter and 12 inches long, the wire being deflagrated by each discharge.

Fig. 28.



The potential of the condenser was measured from time to time by the quadrant electrometer, and from these measurements the quantity passing at each discharge was deduced; they were as follows:—

				Divisions.	
Deflection of electrometer when condenser was fully charged=				200	
,,	,,	after condenser had been discharged	6 times=150		$\frac{4}{6}=8{\cdot}33$
,,	,,	,,	,, 11 ,,	110	$\frac{4}{11}=8{\cdot}18$
,,	,,	,,	,, 15 ,,	80	$\frac{4}{15}=8{\cdot}00$
,,	,,	,,	,, 18 ,,	55	$\frac{4}{18}=8{\cdot}125$
				Mean	8·16

So that, on the average, each discharge took $\frac{8}{200}$, or 4 per cent., of the whole charge; and this quantity, there is reason to believe, is quite as great as that which passed through the rabbit.

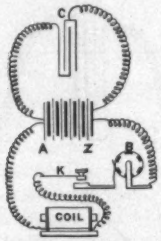
Secondary Current induced by a Primary Current of High Potential.

Our experience with the detector-coil already described, and other smaller coils, all of which gave very long sparks in relation to the current, under the conditions about

to be described, led us to make experiments with one of Apps's usual coils for 6-inch sparks.

The diagram (fig. 29) shows the arrangement of the apparatus: A Z, the battery, is

Fig. 29.



connected *permanently* with the condenser C, A to one plate, Z to the other; the A terminal of the battery is also connected to one terminal of the primary of the coil, the Z terminal to a make-and-break-wheel B, to be worked by hand, thence to the key K, which is connected to the other terminal of the coil.* If the key K is pressed down, and the wheel B is made to rotate, it is evident that a current will pass, or not pass through the primary of the coil, according as a conducting or a non-conducting tooth of the break-wheel is in connexion with the contact spring; but the battery is never disconnected from the condenser by the rotation of the break-wheel; therefore, when the make-and-break-wheel permits of the current passing through the primary of the coil, it is the *accumulated* charge of the condenser which actually passes through it, and hence produces a very exalted effect in comparison to that of the battery alone. Experiments were made with Apps's 819 coil, already described; also with—

Apps's coil, 815.

	Length of wire.	Diam. of wire. inch.	Resistance. ohms.	Turns.
Primary	78 feet	0·06	0·245	270
Secondary	4408 yards	0·0055	2196·000	13,000

and Apps's coil, No. 821, for producing a 6-inch spark:—

	Length of wire.	Diam. of a wire. inch.	Resistance.	Turns.
Primary	66 yards	0·065	0·22	250
Secondary	5¼ miles	0·0068	4900·00	24,000

* The break-wheel B B and key K K' are shown in position, fig. 9, page 63.

On one occasion, with coil 815, in connexion with coil C of 350 yards, 0·028 microfarad, as a condenser, and 3240 powder cells, which evolved 0·3 cub. centim. mixed gases per minute in the voltameter, 3-inch sparks were obtained, with a moderate rotation of the contact breaker.

Apps's No. 821 coil, either with its own condenser or $\frac{3}{4}$ths of Ladd's condenser, D 2 =0·1807 microfarad, produces a rapid succession of 6-inch sparks when worked with 6 cells in series of a zinc-carbon battery, charged with a solution of bichromate of potash and sulphuric acid, the plates being 12 inches by 5 inches, and each zinc between two carbon plates; the make-and-break being effected automatically by the usual hammer-and-anvil arrangement. This battery evolved 152 cub. centims. of mixed gases per minute, when the current passed through a voltameter having a resistance of 17 ohms, and containing a mixture of 1 part sulphuric acid and 10 of water. The chloride of silver battery evolved only 0·5 cub. centim. of mixed gases under the same circumstances, consequently only $\frac{1}{304}$th part; nevertheless, as great or even greater effects were obtained with it than those with the zinc-carbon battery.

With 1080 cells and the Ladd condenser D 2, 0·4518 microfarad, connected permanently with the battery, a dense spark, 3·5 inches long, was obtained on making contact with the key, so as to send the accumulated charge through the primary of the coil, but only a feeble spark on breaking contact.

With 2280 cells and condenser D 2, under the same circumstances, a full 6-inch spark was obtained, and a rapid succession of such sparks when the break-wheel made 44 contacts in a second.

With 3480 cells, on making contact, the same effects, and a rapid succession of such sparks when the break-wheel made 62 makes-and-breaks in a second.

It seemed probable that the battery could charge up larger condensers with sufficient rapidity, and this was shown to be the case by the following experiments:—

With 3480 cells and condensers D 2 and D 3, 0·9222 microfarad, dense sparks not only passed between the terminals of the secondary coil, but other sparks, longer than 6 inches, jumped from every part of the coil when the break-wheel made 212 contacts in a second.

With the same number of cells and condensers D 1, 2, 3, 4, 1·4887 microfarads and 352 breaks in a second, the sparks were as long, but denser, than in the last-named case.

It appears from the foregoing experiments that a high potential is very favourable to the production of induction effects when used in connexion with accumulators of suitable capacity. The *accumulated* high-tension charge passes at each make contact, and produces effects partly dependent on the potential and partly on the quantity of current, which must be, however, considerably less in a given time than that when a battery of large plates is employed (6 zinc-carbon cells, 12×5 inches).

Although it was not anticipated that the production of these exalted effects in comparison with the current was due to any effect with regard to the induced magnetism

in the iron core, nevertheless some direct experiments were made to test this point.

A horse-shoe electro-magnet, weighing 1854 grains (0·265 lb.), surrounded with 1102 yards of insulated copper wire of 0·014 inch diameter, in 4352 turns and 34 layers, and presenting a total resistance of 200 ohms, consequently very small in comparison with the internal resistance of the batteries, was employed in making the experiments. The armature was suspended on a delicately-poised steel-yard, accurately divided, and provided with a suspender for the weight, mounted on rollers to permit of its being moved smoothly along the long arm of the lever, so as not to give any shock which might disturb the armature.

Observations were made of the weight supported by the magnet when 1200, 2400, and 3600 cells were used, the current passing in each case being at the same time measured by a galvanometer, the value of whose deflections had been determined in absolute units of current. The following results show that the weight supported by an electro-magnet was not merely proportional to the current, but increased with the number of cells :—

Number of cells (col. 1).	Current (col. 2).	Weight supported (col. 3).	Col. 3. / Col. 2. Weight in lbs. per Weber.	Ratio to 1200 cells as unity.
	Weber.	lbs.		
1200	0·09443	26·6	281·6	1·000
2400	0·09261	32·3	340·9	1·211
3600	0·08298	31·5	379·6	1·348

Other experiments were made with an electro-magnet formed of the same core, but with the substitution of coils composed in all of 37·6 yards of insulated copper wire, 0·052 inch diameter, in 246 turns, and having a resistance of 0·6 ohm. The results obtained confirm the statement that the weight supported increases with the number of cells for the same current :—

Number of cells (col. 1).	Current (col. 2).	Weight supported (col. 3).	Col. 3. / Col. 2. Weight in oz. per Weber.	Ratio to 1200 cells as unity.
	Weber.	oz.		
1200	0·10660	66	619·0	1·000
2400	0·08898	63	707·9	1·144
3600	0·08399	62	738·2	1·192

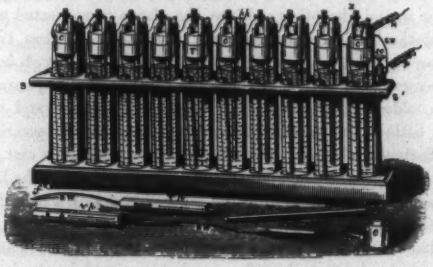
This electro-magnet, with the last-named coil composed of 37·6 yards, supported 42 pounds when the zinc-carbon battery of six cells in series, described at page 92, was connected with it, giving a current of 14·35 Webers. The weight divided by the current comes out 46·8 as the weight in ounces per Weber. The foregoing results must not be accepted as *final*, as the experiments will be repeated at a future opportunity.

Description of the Battery and its Working.

We now proceed to give some account of the battery, of the working of which we have had nearly three years' continuous experience.

As originally constructed, the chloride of silver battery had open cells, and the zinc element was amalgamated;* since then we have constructed batteries in which the cells (tubes) were closed with vulcanised rubber stoppers, perforated to admit of the insertion of the zinc rod, the silver wire connected with the chloride of silver was inserted between the stopper and the side of the tube, it being previously covered with several folds of thin sheet gutta-percha to protect it from the action of sulphur in the vulcanised stopper. The amalgamation of the zinc has the advantage of preventing, to a great extent, the strong adherence of the oxychloride of zinc to which we have referred in an early part of the paper, but presents the great disadvantage of amalgamating and ultimately rotting the thin flattened silver wire ;† so that having to choose between two evils,

Fig. 30.



we have preferred not to amalgamate the zinc when it is intended to keep the batteries one or more years in action. Fig. 30 shows a nest of 20 rod cells of the most recent construction already described,‡ but of which we have not before given any drawing. The several components of the battery are shown at the base of the stand: Z, the zinc rod with the plug *p*, inserted in a hole at the right-hand end; AgCl, the chloride of silver rod, cast on the flattened silver wire SW; V*p*, a vegetable parchment cylinder, open at both ends and perforated towards the top with two holes to admit of the silver wire SW being interlaced through them, as shown in the figure immediately above it;

* Journal of the Chem. Soc., new series, vol. vi., entire series, vol. xxi. p. 488, 1868.

† Platinum, which would not amalgamate, might be substituted, but it would cost £55 extra per 1000 cells.

‡ Proc. Roy. Soc., vol. xxiii. p. 357.

the vegetable parchment is made to adhere so as to form a cylinder by means of shell-lac varnish on the edge of the last layer, of which there are three of one continuous piece; as the shell-lac varnish does not effectually secure the adherence of the vegetable parchment (for nothing does it effectually) a few stitches of thread are made at the lower end, the interlacing wire preventing the vegetable parchment from unfurling at the upper part. The use of the vegetable parchment cylinder is to prevent contact between the zinc rod and the chloride of silver; C is the paraffin stopper perforated with two holes, one for the zinc rod to pass through, the other for filling in the liquid, the second hole is ultimately stopped by a paraffin plug *pp*.*

The stand S S′, $16\frac{1}{4} \times 3\frac{1}{2}$ inches and $4\frac{1}{2}$ inches high, is made of Honduras mahogany and holds 20 cells; it is supported on four ebonite feet *f*, *f*, $\frac{1}{2}$ inch high; on the top rail at the right or left corner, for the alternate shelves of the cabinet, is fixed a screw-clamp *sc* supported on a cylinder of ebonite fitted in the stand, the silver wire SW of the last cell is inserted between the screw-clamp and this ebonite support, and held fast by screwing the clamp tightly into its support. The zinc of the terminal cell has also a screw-clamp screwed on it. The zinc terminal clamp of one tray of 20 cells is connected by a gutta-percha covered wire N, one end being inserted and screwed fast into it, and the other end into the clamp *sc* connected with the silver wire of the terminal cell of the adjoining tray. The cells are glass tubes with flat bottoms, $5\frac{1}{2}$ inches high and $1\frac{1}{4}$ inch in diameter; they pass through holes in the top rail and into recesses in the bottom of the stand. When the trays are put together a hot iron, like a soldering-bit, is run round the edge of the tube and round the zinc rod, this melts a little of the paraffin, making the joint tight and securing the zinc in its place. The flattened silver, on which the chloride of silver is cast, of one cell is connected with the zinc of the adjoining cell by passing it through the hole in the top of the rod, and securing it by pressing in the taper plug *p* with a pair of pliers; these wires are 8 inches (20·32 centims.) long, 0·05 inch (0·127 centim.) wide, and 0·009 inch (0·0229 centim.) thick, and weigh each 13·53 grains (0·88 grm.). The holes in the stopper for charging the tubes are lightly closed by the insertion of the small paraffin plug *pp*, when the liquid has been inserted. The chloride of silver rods† are 2·125 inches (5·4 centims.) long, and 0·3 inch (0·762 centim.) diameter, and weigh 200·12 grains (12·97 grms.); the vegetable parchment cylinders are 3·8 inches (9·65 centims.) long, and 0·44 inch (1·12 centims.) diameter. The zinc rods are

* The zinc rod is procured from the Belgian Vieille Montagne Zinc Company; the chloride of silver rods, cast on the silver wires from Messrs. Johnson and Matthey, Hatton Garden; the paraffin stoppers from Messrs. Field, Paraffin Works, Lambeth Marsh; the stands from Messrs. Tisley and Spiller, No. 172, Brompton Road, who are prepared to supply all the materials, and also to make the battery complete; the glass tubes from Mr. Hicks, No. 8, Hatton Garden, and Messrs. Negretti and Zambra, Holborn Viaduct.

† The cast chloride of silver rods and the silver wires for 1366 cells cost £140 3*s*. 10*d*. = 2*s*. per cell, including the labour of casting.

6 inches (15·24 centims.) long, and 0·22 inch (0·56 centim.) diameter, and perforated at the top with a hole 0·1 inch (0·25 centim.) in diameter, to admit the silver wire of the adjoining cell.

The fluid used for charging the batteries is chloride of ammonium, 23 grms. to 1 litre of distilled water; by making use of a glass siphon with a long arm of india-rubber tubing, provided with a pinch cock, and terminating in a glass tube drawn down to enter freely into the hole in the paraffin stopper, it was found that 2400 cells could be charged by one person in ten hours.

Generally an enormous breakage of tubes takes place, the smaller number while inserting the stopper, but far the greater number without any apparent cause, in many cases after filling in the fluid, but chiefly before the battery has been charged. This is a serious trouble, for as much as 33 per cent. of breakage occurs, and arises mainly from the tubes not having been properly annealed.

The battery behaves, on the whole, extremely well, and all the better the more frequently it is used, for idleness is its bane, as it permits of the slow formation and close adhesion of a skin of oxychloride of zinc, which interposes an enormous resistance in each cell, and reduces the current sensibly when the battery is worked in circuits of small resistance; but for experiments with vacuum tubes, the current is amply sufficient, and has, in most cases, to be reduced by external resistance in order to protect the terminals of the tubes from fusing. It is remarkably constant, and if coupled up through a resistance with a galvanometer in circuit, the deflection of the needle has been found to remain constant for several hours; this we have had frequent occasion to do when determining the value of the deflections of our galvanometers in absolute units by electrolysis. For example, a battery of 10 elements in series was connected through two galvanometers to a decomposition cell containing a solution of 1 part crystals of silver nitrate and 5 parts of water; both electrodes were of silver, and were weighed before the commencement and at the end of the experiment. The current was continued for exactly 1 hour, during which time one galvanometer showed a constant deflection of 77°·75, the other with fewer coils 60°·75, when it was found that—

The positive electrode had lost 0·617 grm., and
The negative electrode had gained 0·616 „

Mean 0·6165 „

$$\frac{0{\cdot}6165}{3600} = 0{\cdot}0001713 \text{ grm. per second.}$$

The resistance of the battery was 55 ohms, that of the decomposition cell was 3 ohms, and that of two galvanometers together was 5·24 ohms, making a total resistance of 63·24.

$$\frac{0{\cdot}0001713 \times 63{\cdot}4}{10} = 0{\cdot}0010833 \text{ grm. of silver per second,}$$

reduced by 1 cell with a resistance of 1 ohm.

A similar experiment with acidulated water in a voltameter having a resistance of 20 ohms gave in 6 minutes 7·2133 cub. centims. of mixed gases at 0° Cent. and 760 millims; this corresponds to 0·001035 grm. of silver reduced per second by 1 cell through a resistance of 1 ohm, showing, on the supposition that the resistance had been accurately ascertained, that in the latter case about 5 per cent. of the current passed without an equivalent evolution of the mixed gases.

In order to eliminate small errors in the determination of the internal resistance of the battery, a single cell was built up of 10 rod cells so as to form one element of small resistance, namely, 0·297 ohm; it was coupled up to the nitrate of silver decomposition cell through various resistances, making from 1·672 to 106·175 ohms total resistance in the circuit, the deflection of the galvanometers remained constant for 30 hours. The mean of four experiments gave 0·0010945 grm. of silver deposited per second by 1 AgCl cell through 1 ohm. This amounted to 94 per cent. of KOHLRAUSCH's number multiplied by 1·03 volt, the electro-motive force of the chloride of silver cell—

$$\frac{0{\cdot}011363^{*} \times 1{\cdot}03}{10} = 0{\cdot}0011704,$$

KOHLRAUSCH's number being for the C. G. S. electro-magnetic unit, of which the Weber is one-tenth.

When the deposit of oxychloride has caused a greater reduction of current than is convenient, the battery may be restored to its original condition by scraping the zinc rods, which is easy of accomplishment; thus, 2400 rod cells charged up December 15th, 1875, after being short-circuited for about half-an-hour to start the battery, evolved in a voltameter 2 cub. centims. of mixed gases in a minute; on April 9th, 1877, the battery only evolved 0·45 cub. centims. per minute. Twenty cells were taken to pieces, and the zinc rods scraped to remove the crust which had formed on them, this battery of 20 then evolved 2·85 cub. centims. per minute. The whole of the batteries were subsequently taken to pieces, and the zinc rods scraped; it required, on the average, six days to take to pieces and re-make up each 1200 cells of the rod battery.† From each of the batteries, 6 and 7, each containing 1200 cells, there was

* EVERETT's C. G. S. Units, p. 77.

† This operation was conscientiously performed by a pupil and workman of Messrs. TISLEY and SPILLER, Mr. HENRY HAWKINS, who has put together most of our batteries, and of whose zeal and intelligence we are able to speak in high terms.

Since this communication was sent in, it has been found that a more expeditious mode of restoring the battery to its original current force is to withdraw the small paraffin plug used to close the hole in the stopper through which the cells are charged, and to introduce into each cell, containing 50 cub. centim., 1 cub. centim. of pure hydrochloric acid, sp. gr. 1·16, containing 31·8 per cent. HCl gas,

removed 514 grms. oxychloride of zinc ten months after charging; from battery 5, of 1200 cells, 894 grms.; and battery 4, 1200 cells, 809 grms., sixteen months after charging. This deposit is in hexagonal plates, and on analysis was found to have the following composition:—15 ZnO, 3 $ZnCl_2$ + 20 H_2O.

	Theory.		Found.		
18 Zn	1173·6	59·07	58·33	58·33	
15 O	240·0	12·08			
6 Cl	213·0	10·72	11·82	11·82	11·40
20 H_2O	360·0	18·13	17·40	16·20	
	1986·6	100·00			

The formation of oxychloride of zinc is not peculiar to the chloride of silver battery, but takes place in all batteries where the zinc is immersed in a solution of a neutral chlorine compound (zinc chloride, sodium chloride, ammonium chloride).

We found the vulcanised stoppers to be a source of great trouble; in the first place, their elasticity frequently causes the tube to split, not at first possibly, but after the lapse sometimes of many months. Moreover, after a year or so, many of them become in some measure conducting, and slowly run down the cell, and we have had many cases where a current of high potential has run along the top, and set fire to the stopper. We have, therefore, entirely discarded vulcanised stoppers, substituting paraffin in our recent batteries and replacing broken down cells with vulcanised stoppers by others with paraffin. The paraffin stoppers may be cast solid, as they are easily bored in a lathe with the American drill; generally about five sizes are requisite to suit the various dimensions of the tubes used for cells, for it is quite impossible to obtain them of uniform diameter.

After having been in almost daily use during ten months, it was found that, in batteries 6 and 7, 3·57 grms. of the chloride of silver rod, weighing originally 13 grms., had been reduced, and 4·57 in batteries 4 and 5, which had been in use sixteen months; so that, when once set up, the life of the battery is sufficiently long, say three years, to admit of a great variety of experiments being made with it before it becomes necessary to renew it. The loss of silver is not great, and on this point we are able, in consequence of an accidental circumstance, to give precise information; 600 powder cells which had been charged up each with 14·5 grms. chloride of silver, ran down in consequence of portions of the zinc rod falling down on to the chloride

equivalent to 0·3689 grm. acid. It is better to dilute the acid with an equal volume of distilled water before introducing it into the cells, which is conveniently done by means of a graduated pipette furnished with a stop cock. An effervescence takes place, and it is therefore necessary to allow the tubes to remain twenty-four hours without the small paraffin plug being replaced, in order to permit the hydrogen, which is generated, to escape; the acid dissolves 0·3293 grm. of zinc, or its equivalent of oxide. It required two days for each battery, 1200 cells, to perform this operation.—Nov. 29, 1877.

(this is now obviated by placing six discs of vegetable parchment on the chloride), the total weight of silver contained in the charge was—

$$\frac{600\times14{\cdot}5\times15{\cdot}4325\times3}{480\times4}=209{\cdot}78 \text{ troy ounces of silver.}$$

The quantity recovered was 206·92

Loss 2·86 or 1·38 per cent.

Working in a large way this percentage, though small, would be still diminished, so that the chloride of silver battery is not costly in its working; and we venture to believe that it is destined yet to find a place in telegraphy, for which its great constancy, and the very little attention it requires, particularly suit it. It is without question a valuable implement for scientific research, and a source of great comfort to the operator, who finds it always ready at hand whenever he enters the laboratory.

Both the iodide and bromide batteries appear to form a much larger quantity of an oxyhaloïd compound than the chloride; the iodide solution especially seems to act on the zinc rods, causing filaments of metal to form, and bridge across towards the iodide of silver element. They may be useful in making up in combination with chloride cells a battery of an exact number of volts, thus—

	volts.
3 cells chloride = 3 × 1·03 =	3·09
1 cell bromide	0·908
	3·998
Average per cell	0·9995

The Discharge in Air at Pressures less than the Ordinary Atmospheric Pressure.

Only a few experiments have as yet been made by us on the length of spark at different pressures below that of the atmosphere, but we intend to pursue this investigation with a micrometer discharger of longer range than that shown in fig. 1, page 58. The following results were obtained with our present means with a point and a disc and 8040 cells:—

Pressure. millims.	Fraction of an atmosphere.	Length of spark. inch.	Ratio to length at 1 atmosphere.	Ratio of length of spark to dilatation.
760	$\frac{1}{1}$	0·34	1	$\frac{1}{1}$ = 1·0000
326·82	$\frac{1}{2\cdot326}$	0·68	2	$\frac{2}{2\cdot326}$ = 0·8598
229·17	$\frac{1}{3\cdot316}$	1·02	3	$\frac{3}{3\cdot316}$ = 0·9046
197·29	$\frac{1}{3\cdot853}$	1·19 (limit)	3·5	$\frac{3\cdot5}{3\cdot853}$ = 0·9086

so that with a point and a disc the length of spark is not precisely in the inverse ratio of the pressure.

With two spherical surfaces, each of 3 inches radius of curvature and 1·5 inch diameter, the following results were obtained with 8040 cells :—

Pressure. millims.	Fraction of an atmosphere.	Length of spark. inch.	Ratio to length at 1 atmosphere.	Ratio of length of spark to dilatation.
760	$\frac{1}{1}$	0·079	1·00	$\frac{1}{1} = 1·000$
602	$\frac{1}{1·263}$	0·100	1·26	$\frac{1·26}{1·263} = 0·999$
414·7	$\frac{1}{1·833}$	0·200	2·52	$\frac{2·52}{1·833} = 1·375$
299·5	$\frac{1}{2·537}$	0·400	5·04	$\frac{5·04}{2·537} = 1·986$
141·5	$\frac{1}{5·370}$	0·800	10·08	$\frac{10·08}{5·370} = 1·876$

With spherical surfaces the spark is longer in the last three cases than it would be if in the inverse ratio of the pressure ; nearly, indeed, twice as long when the pressure is reduced to about two-fifths.

The comparison between the striking distances with spherical surfaces, and with the point and disc, points to the probability of the distances coinciding at a certain degree of rarefaction.

Note A.

"I should attribute the difference of adhesion of the paper to the plate according as the point was positive (P) or negative (N) to the different facility with which electricity passes by discontinuous, and not too rapidly succeeding, discharges from points P and N ; the facility being much greater from the former. The points I have in view are not the metallic point alone, but also those ends of the fibres of which the paper consists which happen to be at the surfaces. The dried paper is a very bad conductor. Its upper surface is electrified by the electrified air whether the metallic point is P or N, and the electricity passes down through the bad conductor so slowly that the supply of electricity from the electrified air suffices to keep up a good charge on it. When the metallic point and consequently the paper is P, the ends of the fibres and other little roughnesses on the under face of the paper, by the property of P points, part with their electricity readily to the plate, so that the under portion of the stratum of paper is pretty well free from charge. When it is N, the negative electricity of the paper has much greater difficulty in passing into the plate, and therefore there is more charge in the paper, and that too is situated (in the mean) further down, so that the paper and plate are equivalent to a condenser thinner than the paper itself, and therefore capable of receiving a greater charge than a metallic plate whose lower surface is at the height of the upper surface of the paper, and which is opposed to the actual plate, the paper being supposed removed.

"When the paper is damp, it conducts so much better that the electrification by the electrified air cannot keep pace with the loss by transfer to the plate, and there is small charge, and therefore small attraction. When the upper electrode is greatly curved there is little electrification of the air, and therefore the charge of the paper resting on the lower electrode could not be kept up."

Supplement.

February 11, 1878.

On January 1st, 1878, we charged up with liquid the 2960 cells we had been preparing during the four previous months; 1500 of these were rod cells, and 1460* powder cells. Before combining them with the 8040 cells already in use we had the latter thoroughly examined and defective elements renewed. Advantage was taken of the preparation of the new cells in order to ascertain whether the old ones had retained their initial electro-motive force; this was done by means of the quadrant electrometer referred to in the footnote to page 104, one pole of each battery being connected to earth, the other to the induction plate of the electrometer, and the following numbers were obtained:—

Battery.	No. of cells.	Scale division.
No. 1.	1080 powder.	Deflection per cell=0·1069, made up afresh with new liquid.
2.	1080 „	„ „ =0·1040.
3.	1080 „	„ „ =0·1099, made up afresh with new liquid.
4.	1200 rod	„ „ =0·1008, cells contained 6·8 per cent. $ZnCl_2$.
5.	1200 „	„ „ =0·1046, „ „
6.	1200 „	„ „ =0·1050, „ „
7.	1200 „	„ „ =0·1063, „ „
8.	1500 „	„ „ =0·1110, new battery.
9.	1460 powder	„ „ =0·1096, „

The sum of the deflections of all the batteries equals 1173 scale divisions; the mean deflection per cell of 8 and 9 was 0·1103, therefore $\frac{1173}{0·1103}$=10,640 cells of the potential of the new ones, that the whole 11,000 were equal to when the observation was made.

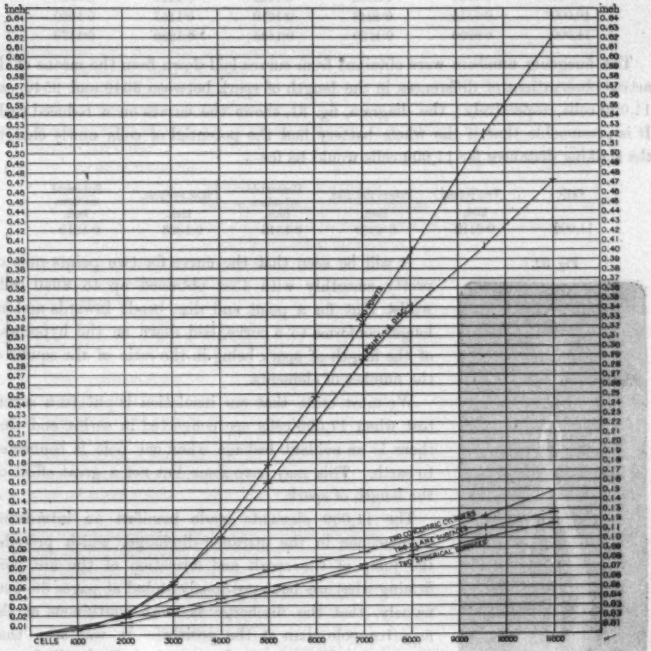
It was found by direct experiment with several of the trays of 20 cells that the formation of $ZnCl_2$ lessened the potential of the battery, and that it could be restored by removing the old liquid and charging the cells with a fresh solution of chloride of ammonium in the ratio of 23 grms. to 1 litre of distilled water.

In giving the following particulars of the measurements of the striking distances, it is necessary to state that as No. 8 battery contains 1500 cells and No. 9 battery 1460 cells, by adding No. 8 and 8 and 9 to the old series of 8040, we obtain 9540 and 11,000 cells respectively. It was not thought necessary to commence all the measurements afresh, as this would have occupied much time and uselessly wasted the life of the battery, so that we have contented ourselves with merely taking the striking distance of the 8040 cells, each time for the several forms of terminals, and then the *additional* striking distance for 9540 and 11,000 cells respectively. These additional lengths of spark we have added on to the several means obtained for 8040 cells, as

* The powder cells will be used to renew any of those in batteries 1, 2, 3 which may become exhausted, and will be replaced by rod cells.

showing more correctly the true striking distances than could be obtained by a few isolated experiments.

Fig. 31.



LENGTHS of Spark.

No. of cells.	Two points.	Point + and disc −	Concentric cylinders.	Plane surfaces.	Spherical surfaces.
	inch.	inch.	inch.	inch.	inch.
8,000	0·4000	0·3400	0·0990	0·0882	0·0818
9,000	0·4760	0·3805	0·1142	0·1020	0·0938
10,000	0·5515	0·4248	0·1310	0·1157	0·1050
11,000	0·6200	0·4730	0·1496	0·1280	0·1170

The foregoing numbers were obtained from curves laid down from the means of the actual observations of differences in the length of spark between 8040 and 9540, and 11,000 cells respectively; the diagram, fig. 31, shows the curves on a reduced scale. It is presumable that if the whole battery had the potential of cells newly charged the striking distances for 11,000 cells would be for—

Cells.	Two points.	Points and disc.	Concentric cylinders.	Plane surfaces.	Spherical surfaces.
	inch.	inch.	inch.	inch.	inch.
11,000	0·6412	0·4889	0·1546	0·1323	0·1210

Fig. 32.

It will be seen that the curve for two points runs on pretty smoothly with that obtained up to 8040 cells, whilst that for a point and disc bends inwards and no longer conforms to a curve, laid down on the hypothesis of the length of spark being in the ratio of the square of the number of elements.

We must state that our insulation is put to a severe test when 11,000 cells are connected in series, and that there is an evident leakage when one pole is connected to earth. This may have some but not a great effect on the length of spark.

The 11,000 elements made manifest an interesting phenomenon in the streamer-discharge, which precedes the jump of the spark and formation of the arc, confirming what we have previously stated at pages 88–100, namely, that the discharge is more continuous at the negative pole than at the positive. It was seen that when two points were used as terminals in the discharger (fig. 1, page 58) with this number of elements there was a continuous brush-discharge at the negative, while from the positive an intermittent streamer-discharge took place, and that the streamers emanating from it enveloped the negative brush-discharge without in the least disturbing its form. This phenomenon is well represented on a scale of 4 to 1 in fig. 32.

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VI. *On the Tides at Malta.*

By Sir G. B. Airy, *K.C.B., F.R.S., Astronomer Royal.*

Received July 14,—Read December 6, 1877.

Section I.—*Introduction.*

Admiral Sir Astley Cooper Key, K.C.B., late Superintendent of the Royal Naval College at Greenwich, and formerly Naval Commander of Malta, before leaving this country for a foreign station, placed in my hands the original record of tidal observations made by a self-registering tide-gauge at La Valetta, extending through one entire lunation and through parts of others. On the location and construction and use of the instrument I have received from Sir Cooper Key the following notes :—

"The place of the tide-gauge was about 40 or 50 yards from the entrance of the Somerset Dock (which is in the French Creek, so called by us), on the western side or left hand when entering the dock. A channel about a yard wide, and 8 or 10 yards long, led to a deep recess in which the gauge was placed. No ripple was felt from the effect either of wind or of ships moving in the neighbourhood.

"The float was a copper vessel, nearly spherical, about 8 inches in diameter; a vertical rod attached to it passed freely through a guide, and was hinged to the end of a horizontal lever, of which the arms were so proportioned that each space marked on the tabular form between the horizontal lines [one-fourth of an inch.—G.B.A.] corresponded accurately to an inch rise or fall of the float. Care was taken to ensure that the reading on the horizontal-zero line always corresponded to a definite height of water. [I remark here that the base-line or zero of horizontal measures is printed on the sheets, and that there is no other base-line given by a pencil attached to the fixed part of the instrument frame; I shall refer to this circumstance hereafter.—G.B.A.] I can depend on the accurate movement of the float. I have often watched the instrument.

"The cylinder on which the paper was wrapped revolved once in 24 hours [the corresponding length of paper is 20 inches.—G.B.A.], and was adjusted every morning when the paper was removed. The accuracy of the movement was however dependent on clockwork. The distance between the vertical lines on the sheets was intended to represent solar hours. The time was not taken with accuracy, but is intended to represent mean solar time at Valetta. The hours given between the lines, such as 8 A.M., &c., merely indicate that the register of the height of the water midway

between the vertical lines was intended to correspond with the hours marked above the space."

The consecutive sheets were pasted together, forming a band nearly 60 feet long. For easy control of this I mounted it on two rollers. On examination the record appeared to be everywhere in general good order, with the one exception, that on April 5, 1871, there are 25 hour-spaces, as if the barrel had been slipped by hand while the pencil was in contact. I suppressed one hour-space in the part which appeared to require it, and the record of that day then accorded sufficiently with those adjoining.

Section II.—*First Treatment of the Registers for Removal of Oscillations of Short Periods, and for Measures referring to the Tides at London.*

Through many parts of the register the course of the pencil, as it would have been guided by luni-solar tides only, is disturbed by vertical oscillations (for which I anticipate the name *seiches*), with a sensibly uniform period of about 21^m, and with magnitude sometimes considerably exceeding that of the genuine tides. To liberate the tides from the *seiches*, the highest and lowest points of each oscillation were marked, and the intermediate point was carefully determined by compasses, and was marked; a pencil curve was then drawn through all these intermediate points, which was considered to be the true tidal curve. The number of intermediate points thus determined was nearly 1100.

The base adopted in the numerical evaluations of the height of the water (to be shortly treated) was 10 inches below the zero line of the printed register sheets; this base was adopted in order that all records of tidal elevation might have the positive sign.

For the treatment of the measures in regard to time, I determined to lay aside all consideration of harmonic sequence of arguments, and to compare every day's tide with the corresponding tide at London. The reasons for doing so were mainly these: that in fact each day's tide is sensibly independent of every other day's tide; that the tide of the Thames is a very convenient standard, because it contains no sensible trace of diurnal tide, and that in the Admiralty Tide Tables we have (as is generally understood) a fairly accurate statement of the real tides at London.

Interpreting the scale of times upon the sheets in conformity with Sir Cooper Key's description above, and then considering those times as London times (thus introducing an error depending on difference of longitude, which is unimportant, because it can be corrected at the end), I laid down by points on the printed base-line the time of every London high water. The intervals between these points were divided each into 24 equal parts, and these were taken as corresponding to genuine tidal half-hours. At every one of these points the elevation of the tidal register was measured on the sheet. The number of these measures is about 1900.

Now, considering that the quantities of which we are in search are either constant

through the tidal day (as the mean height of the water for the day) or are assumed to be periodical in the course of the tidal day (as the semidiurnal and diurnal tides in height), it is evident that we shall obtain all that is necessary for determination of the several coefficients of those quantities, by dividing the 48 measures made on each tidal day into 8 groups, each of 6 measures, and taking the mean for each group. The further treatment of these will be the subject of the next section.

The tables below exhibit the means for each of the 8 groups on each day, and these numbers are the base of all the subsequent calculations. It is to be remarked that the "Zero of Tidal Time" is 16^m earlier than the time of London high water, for the following reason:—The first measure of height on the tidal day was taken at the time of London high water, and the last was taken 30 tidal minutes before the following London high water. The means for the several groups therefore correspond to times 15 tidal minutes or 16 solar minutes earlier than the tidal hours (at intervals of 3^h), beginning with London high water. By fixing the "Zero of Tidal Time" 16 minutes earlier than London high water, the proper relation is established between the means of the groups and the subdivisions of the tidal day.

MEANS, for every group of three tidal hours, of the six half-hourly elevations of the tidal water in each of these groups, recorded at Malta, 1871 and 1872.

Commencement of the Tidal Day, or Zero of Tidal Time, in Malta Mean Solar Time.	No. of Group.	Mean of Six Elevations.	Commencement of the Tidal Day, or Zero of Tidal Time, in Malta Mean Solar Time.	No. of Group.	Mean of Six Elevations.	Commencement of the Tidal Day, or Zero of Tidal Time, in Malta Mean Solar Time.	No. of Group.	Mean of Six Elevations.
1871 h. m.		in.	1871 h. m.		in.	1871 h. m.		in.
Mar. 31 .. 22 22	1	10·88	April 4 .. 1 19	1	11·93	April 7 .. 3 13	1	12·23
	2	11·15		2	11·83		2	9·87
	3	9·07		3	7·15		3	5·62
	4	8·83		4	8·12		4	7·05
	5	12·62		5	12·53		5	9·18
	6	12·68		6	9·68		6	6·75
	7	9·72		7	5·85		7	4·12
	8	9·10		8	8·97		8	6·62
April 1 .. 23 42	1	12·55	April 5 .. 1 56	1	13·07	April 8 .. 3 53	1	9·70
	2	12·55		2	10·53		2	8·00
	3	8·73		3	6·32		3	5·33
	4	8·40		4	8·60		4	6·63
	5	12·62		5	12·55		5	8·57
	6	11·90		6	9·38		6	6·85
	7	7·52		7	5·93		7	5·28
	8	8·33		8	9·45		8	7·07
April 3 .. 0 34	1	12·17	April 6 .. 2 34	1	13·32	April 9 .. 4 34	1	9·68
	2	12·22		2	10·12		2	8·85
	3	8·18		3	6·37		3	6·30
	4	8·08		4	9·18		4	7·07
	5	12·52		5	12·03		5	8·55
	6	12·05		6	9·05		6	7·90
	7	7·02		7	6·02		7	6·22
	8	7·57		8	9·02		8	7·23

MEANS, for every group of three tidal hours, of the six half-hourly elevations of the tidal water in each of these groups, recorded at Malta, 1871 and 1872—*continued*.

Commencement of the Tidal Day, or Zero of Tidal Time, in Malta Mean Solar Time.	No. of Group.	Mean of Six Elevations.	Commencement of the Tidal Day, or Zero of Tidal Time, in Malta Mean Solar Time.	No. of Group.	Mean of Six Elevations.	Commencement of the Tidal Day, or Zero of Tidal Time, in Malta Mean Solar Time.	No. of Group.	Mean of Six Elevations.
1871 h. m.		in.	1871 h. m.		in.	1871 h. m.		in.
April 10.. 5 18	1	8·92	April 16.. 12 22	1	10·73	April 22.. 15 50	1	10·67
	2	8·52		2	7·92		2	7·70
	3	6·87		3	5·67		3	5·98
	4	6·77		4	7·40		4	9·40
	5	7·47		5	11·30		5	11·43
	6	7·55		6	9·20		6	9·35
	7	6·97		7	5·58		7	7·47
	8	7·08		8	7·87		8	10·42
April 11.. 6 8	1	8·02	April 17.. 13 7	1	11·30	April 23.. 16 22	1	11·97
	2	8·30		2	8·75		2	10·10
	3	7·80		3	5·70		3	9·03
	4	7·62		4	7·85		4	12·08
	5	8·05		5	12·17		5	13·45
	6	8·45		6	9·75		6	11·57
	7	7·83		7	6·07		7	10·22
	8	7·32		8	8·20		8	12·15
April 12.. 7 7	1	7·72	April 18.. 13 45	1	11·73	April 24.. 16 53	1	13·18
	2	8·08		2	9·35		2	11·80
	3	6·60		3	6·10		3	10·98
	4	5·38		4	10·00		4	12·53
	5	5·80		5	12·62		5	12·93
	6	6·95		6	9·15		6	11·15
	7	6·45		7	6·65		7	9·75
	8	5·52		8	10·33		8	10·62
April 13.. 8 27	1	6·98	April 19.. 14 17	1	12·80	April 25.. 17 26	1	11·77
	2	8·02		2	9·73		2	10·90
	3	6·27		3	7·13		3	10·70
	4	5·38		4	10·32		4	12·07
	5	7·57		5	13·77		5	12·95
	6	8·70		6	10·47		6	12·53
	7	6·57		7	7·00		7	11·52
	8	6·23		8	9·87		8	12·12
April 14.. 9 58	1	8·95	April 20.. 14 49	1	12·65	April 26.. 18 10	1	12·55
	2	9·05		2	9·60		2	11·62
	3	6·28		3	7·02		3	10·85
	4	6·62		4	10·65		4	11·20
	5	10·00		5	12·88		5	11·58
	6	10·03		6	9·47		6	11·42
	7	6·97		7	7·12		7	10·57
	8	7·38		8	9·77		8	10·53
April 15.. 11 23	1	10·80	April 21.. 15 18	1	11·83	April 27.. 19 2	1	11·40
	2	9·35		2	8·88		2	12·05
	3	6·28		3	7·10		3	11·85
	4	7·55		4	10·82		4	11·47
	5	11·17		5	13·27		5	12·85
	6	9·28		6	10·08		6	14·33
	7	5·80		7	7·53		7	12·77
	8	8·07		8	9·77		8	11·20

MEANS, for every group of three tidal hours, of the six half-hourly elevations of the tidal water in each of these groups, recorded at Malta, 1871 and 1872—*continued*.

Commencement of the Tidal Day, or Zero of Tidal Time, in Malta Mean Solar Time.	No. of Group.	Mean of Six Elevations.	Commencement of the Tidal Day, or Zero of Tidal Time, in Malta Mean Solar Time.	No. of Group.	Mean of Six Elevations.	Commencement of the Tidal Day, or Zero of Tidal Time, in Malta Mean Solar Time.	No. of Group.	Mean of Six Elevations.
1871 h. m.		in.	1872 h. m.		in.	1872 h. m.		in.
April 28.. 20 18	1	12·15	June 10.. 16 50	1	13·47	July 6 .. 2 30	1	
	2	12·02		2	10·43		2	
	3	9·88		3	10·80		3	10·47
	4	8·95		4	12·85		4	14·22
	5	10·68		5	14·48		5	16·33
	6	11·35		6	12·20		6	12·33
	7	8·70		7	10·90		7	9·35
	8	8·12		8	12·73		8	13·27
April 29.. 21 42	1	11·57	June 27.. 19 20	1	13·93	July 29.. 21 42	1	15·03
	2	11·87		2	13·35		2	13·70
	3	8·63		3	10·87		3	11·93
	4	8·85		4	11·07		4	12·47
	5	12·10		5	13·10		5	13·95
	6	12·18		6	12·22		6	11·72
	7			7	10·10		7	
	8			8	11·02		8	
1872								
June 8 .. 15 39	1		June 29.. 21 26	1	14·52	Aug. 29.. 10 16	1	16·48
	2			2	13·65		2	16·52
	3	7·85		3	10·72		3	12·83
	4	11·33		4	12·07		4	13·73
	5	12·18		5	13·77		5	16·37
	6	8·85		6	12·68		6	
	7	7·98		7	10·80		7	
	8	11·07		8	12·20		8	
June 9 .. 16 14	1	12·15	June 30.. 22 26	1	15·70			
	2	9·67		2	15·55			
	3	9·88		3	12·57			
	4	12·87		4	12·13			
	5	13·10		5	15·35			
	6	10·82		6	14·48			
	7	9·53		7	11·02			
	8	11·75		8				

Section III.—*Treatment of the Means of the Grouped Measures, in order to express the Elevation of the Water by the Combination of Mean Height with Semidiurnal and Diurnal Tides.*

Put G1, G2 . . . G8 for the successive means of grouped measures, as exhibited in the last table, for any one tidal day. And put θ for the tidal angle, proportional to the time, whose value is 0 at the commencement of the tidal day, and is 2π at the end of it. Then the values of θ for the six measures of the first group are $\frac{\pi}{48}, \frac{3\pi}{48}, \frac{5\pi}{48}, \frac{7\pi}{48}, \frac{9\pi}{48}, \frac{11\pi}{48}$. And assume that any tidal elevation is to be expressed by

$$M+P\sin 2\theta+Q\cos 2\theta+p\sin\theta+q\cos\theta,$$

(where the second and third term express semidiurnal tide, and the fourth and fifth express diurnal tide). Then the several measures of elevation in the first group are

$$M+P\sin\frac{\pi}{24}+Q\cos\frac{\pi}{24}+p\sin\frac{\pi}{48}+q\cos\frac{\pi}{48}$$

$$M+P\sin\frac{3\pi}{24}+Q\cos\frac{3\pi}{24}+p\sin\frac{3\pi}{48}+q\cos\frac{3\pi}{48}$$

* * * * * *

$$M+P\sin\frac{11\pi}{24}+Q\cos\frac{11\pi}{24}+p\sin\frac{11\pi}{48}+q\cos\frac{11\pi}{48};$$

and, summing these columns vertically, and dividing by 6,

$$G1=M+\frac{P}{12\sin\frac{\pi}{24}}\left(\cos 0-\cos\frac{12\pi}{24}\right)+\frac{Q}{12\sin\frac{\pi}{24}}\left(-\sin 0+\sin\frac{12\pi}{24}\right)$$
$$+\frac{p}{12\sin\frac{\pi}{48}}\left(\cos 0-\cos\frac{12\pi}{48}\right)+\frac{q}{12\sin\frac{\pi}{48}}\left(-\sin 0+\sin\frac{12\pi}{48}\right)$$

similarly

$$G2=M+\frac{P}{12\sin\frac{\pi}{24}}\left(\cos\frac{12\pi}{24}-\cos\frac{24\pi}{24}\right)+\frac{Q}{12\sin\frac{\pi}{24}}\left(-\sin\frac{12\pi}{24}+\sin\frac{24\pi}{24}\right)$$
$$+\frac{p}{12\sin\frac{\pi}{48}}\left(\cos\frac{12\pi}{48}-\cos\frac{24\pi}{48}\right)+\frac{q}{12\sin\frac{\pi}{48}}\left(-\sin\frac{12\pi}{48}+\sin\frac{24\pi}{48}\right)$$

$$G3=M+\frac{P}{12\sin\frac{\pi}{24}}\left(\cos\frac{24\pi}{24}-\cos\frac{36\pi}{24}\right)+\frac{Q}{12\sin\frac{\pi}{24}}\left(-\sin\frac{24\pi}{24}+\sin\frac{36\pi}{24}\right)$$
$$+\frac{p}{12\sin\frac{\pi}{48}}\left(\cos\frac{24\pi}{48}-\cos\frac{36\pi}{48}\right)+\frac{q}{12\sin\frac{\pi}{48}}\left(-\sin\frac{24\pi}{48}+\sin\frac{36\pi}{48}\right)$$

* * * * * *

$$G8=M+\frac{P}{12\sin\frac{\pi}{24}}\left(\cos\frac{84\pi}{24}-\cos\frac{96\pi}{24}\right)+\frac{Q}{12\sin\frac{\pi}{24}}\left(-\sin\frac{84\pi}{24}+\sin\frac{96\pi}{24}\right)$$
$$+\frac{p}{12\sin\frac{\pi}{48}}\left(\cos\frac{84\pi}{48}-\cos\frac{96\pi}{48}\right)+\frac{q}{12\sin\frac{\pi}{48}}\left(-\sin\frac{84\pi}{48}+\sin\frac{96\pi}{48}\right)$$

Substituting the numerical values for the trigonometrical symbols,

$$G1=M+\frac{P}{1{\cdot}5663}\times(+1-0)+\frac{Q}{1{\cdot}5663}\times(0+1)+\frac{p}{{\cdot}7848}\times(+1-\sqrt{\tfrac{1}{2}})+\frac{q}{{\cdot}7848}\times(0+\sqrt{\tfrac{1}{2}}),$$

$$G2=M+\frac{P}{1{\cdot}5663}\times(0+1)+\frac{Q}{1{\cdot}5663}\times(-1+0)+\frac{p}{{\cdot}7848}\times(+\sqrt{\tfrac{1}{2}}-0)+\frac{q}{{\cdot}7848}\times(-\sqrt{\tfrac{1}{2}}+1),$$

$$G3=M+\frac{P}{1{\cdot}5663}\times(-1-0)+\frac{Q}{1{\cdot}5663}\times(0-1)+\frac{p}{{\cdot}7848}\times(0+\sqrt{\tfrac{1}{2}})+\frac{q}{{\cdot}7848}\times(-1+\sqrt{\tfrac{1}{2}}),$$

$$G4=M+\frac{P}{1{\cdot}5663}\times(0-1)+\frac{Q}{1{\cdot}5663}\times(+1+0)+\frac{p}{{\cdot}7848}\times(-\sqrt{\tfrac{1}{2}}+1)+\frac{q}{{\cdot}7848}\times(-\sqrt{\tfrac{1}{2}}+0),$$

$$G5=M+\frac{P}{1{\cdot}5663}\times(+1-0)+\frac{Q}{1{\cdot}5663}\times(0+1)+\frac{p}{{\cdot}7848}\times(-1+\sqrt{\tfrac{1}{2}})+\frac{q}{{\cdot}7848}\times(0-\sqrt{\tfrac{1}{2}}),$$

$$G6=M+\frac{P}{1{\cdot}5663}\times(0+1)+\frac{Q}{1{\cdot}5663}\times(-1+0)+\frac{p}{{\cdot}7848}\times(-\sqrt{\tfrac{1}{2}}+0)+\frac{q}{{\cdot}7848}\times(+\sqrt{\tfrac{1}{2}}-1),$$

$$G7=M+\frac{P}{1{\cdot}5663}\times(-1-0)+\frac{Q}{1{\cdot}5663}\times(0-1)+\frac{p}{{\cdot}7848}\times(0-\sqrt{\tfrac{1}{2}})+\frac{q}{{\cdot}7848}\times(+1-\sqrt{\tfrac{1}{2}}),$$

$$G8=M+\frac{P}{1{\cdot}5663}\times(0-1)+\frac{Q}{1{\cdot}5663}\times(+1+0)+\frac{p}{{\cdot}7848}\times(+\sqrt{\tfrac{1}{2}}-1)+\frac{q}{{\cdot}7848}\times(+\sqrt{\tfrac{1}{2}}-0).$$

As we have here eight equations from which five quantities are to be determined, it is proper to refer to the considerations of the Theory of Probable Errors. Put e for the numerical value of each of the probable errors $e_1, e_2, \ldots e_8$ of the numbers G1, G2, ... G8. Now to form the final equations, determining p and q, we ought in strictness to form intermediate equations by multiplying the equations above by the coefficients of p and q in those equations; and thus we should obtain results for $\frac{p}{{\cdot}7848}$ and $\frac{q}{{\cdot}7848}$, whose probable errors are $\frac{e}{\sqrt{(8-8\sqrt{\frac{1}{2}})}}$. But if, instead of this, we had multiplied each equation by $+1$ or by -1 so as to make all the coefficients for p positive (and similarly for q), we should have obtained results for $\frac{p}{{\cdot}7848}$ and $\frac{q}{{\cdot}7848}$ whose probable errors are $e\sqrt{\frac{1}{2}}$. This is greater than that found by the first process by only $\frac{1}{13}$ part. The loss of accuracy in this second process is so small, and the gain of convenience and simplicity so great, that I have not hesitated to adopt it.

We now obtain the values of M, P, Q, p, q, by the following combinations :—

$$G1+G2+G3+G4+G5+G6+G7+G8=8\,M,$$

$$G1+G2-G3-G4+G5+G6-G7-G8=\frac{8\,P}{1{\cdot}5663},$$

$$G1-G2-G3+G4+G5-G6-G7+G8=\frac{8\,Q}{1{\cdot}5663},$$

$$G1+G2+G3+G4-G5-G6-G7-G8=\frac{4p}{\cdot7848},$$

$$G1+G2-G3-G4-G5-G6+G7+G8=\frac{4q}{\cdot7848},$$

By these simple formulæ, which are very easy of application, the numbers in the next section are formed.

Section IV.—*Exhibition of the Tidal Elements at Malta, deduced from the Observations of each day by means of the preceding Formulæ, with Astronomical and Tidal Elements at London, for Comparison with those at Malta.*

The places of the sun and moon are taken from the Nautical Almanac; the times of London high water from the Admiralty Tide Tables. The half range of London tide is inferred from the height of high water at London, supposing the mean height of water at London to be 10 feet 1½ inch, which appears to be supported by the language of pages 151 and 155 of the Admiralty Time Tables. The Malta observations following April 29, 1871, are omitted, the series being incomplete.

Positions of the Sun and the Moon, and Elements of Tides at London and Malta.

Solar and Lunar Places and London Tides.									Semidiurnal Malta Tides.								Diurnal Malta Tides.	
Time of High Water at London.	Time of Moon's preceding Transit.	Retard of High Water on Moon's preceding Transit.	Half Range of London Tide.	Moon's Declination at preceding Transit.	Sun's Declination at preceding Transit.	Mean Height at Malta.	Zero of Tidal Time.	Mean Height of Water for the Tidal Day.	Value of P.	Value of Q.	Retard of High Water on Zero of Tidal Time.	Time of High Water.	Retard of High Water on Moon's Transit.	Half Range.	Value of p.	Value of q.
d. h. m.	h. m.	h. m.	ft. in.	° ′	° ′	inches	d. h. m.	inches	inches	inches	h. m.	h. m.	h. m.	inches	inches	inches
1871, March 31 22 38	8 17	14 21	6 4	N. 20 36	N. 4 6	10·50	31 22 22	10·50	2·08	−0·24	3 13	1 35	17 18	2·10	−0·32	−0·44
April 1 23 56	9 8	14 50	7 5	N. 17 21	4 29	10·32	1 23 42	10·32	3·27	+0·04	2 50	2 41	17 33	3·27	+0·37	−0·14
2 0 50	9 59	14 51	8 3	N. 13 0	5 15	9·98	2 0 34	9·98	3·55	0·19	2 54	3 28	17 29	3·55	0·29	−0·36
4 1 35	10 49	14 46	9 10	N. 7 47	5 38	9·51	4 1 19	9·51	3·12	1·38	2 12	3 31	16 42	3·40	0·40	+0·22
5 2 12	11 40	14 32	10 8	N. 1 58	6 1	9·48	5 1 56	9·48	2·98	2·26	1 46	3 42	16 2	3·75	0·23	0·42
6 2 50	12 31	14 19	11 3	S. 3 50	6 24	9·39	6 2 34	9·39	2·73	2·36	1 38	4 12	15 41	3·59	0·56	0·36
7 3 29	13 24	14 5	11 8	S. 9 45	6 46	7·68	7 3 13	7·68	2·87	1·71	1 59	5 12	15 48	3·33	1·59	0·83
8 4 9	14 20	13 49	11 7	S. 15 5	N. 7 9	7·18	8 3 53	7·18	1·72	1·28	1 47	5 40	15 20	2·13	0·37	0·53
9 4 50	15 17	13 33	11 2	S. 19 22	7 31	7·73	9 4 34	7·73	1·60	0·04	2 17	6 51	15 34	1·73	0·39	0·42
10 5 34	16 17	13 17	10 4	S. 22 16	7 53	7·52	10 5 18	7·52	0·94	+0·07	2 52	8 10	15 53	0·94	0·39	+0·56
11 6 24	17 17	13 7	8 11	S. 23 34	8 15	7·93	11 6 8	7·93	0·44	−0·27	4 3	10 11	16 54	0·51	0·02	−0·09
12 7 23	18 16	13 7	7 9	S. 23 13	8 37	6·57	12 7 7	6·57	0·90	−0·72	4 17	11 24	17 8	1·15	+0·60	+0·60
13 8 48	19 13	13 30	6 10	S. 21 22	8 59	6·97	13 8 27	6·97	1·33	−0·67	3 53	12 20	17 7	1·48	−0·48	−0·03
14 10 14	20 7	14 7	7 1	S. 18 17	9 21	8·17	14 9 58	8·17	2·11	+0·12	2 54	12 52	16 45	2·11	−0·69	−0·11
15 11 39	20 57	14 42	7 10	S. 14 14	N. 9 42	8·54	15 11 23	8·54	2·53	1·35	2 4	13 27	16 30	2·87	−0·07	−0·05
16 12 58	21 43	14 55	8 9	S. 9 32	10 4	8·21	16 12 22	8·21	2·48	1·75	1 50	14 12	16 29	3·05	−0·44	−0·29
17 13 23	22 28	14 55	9 7	S. 4 41	10 25	8·73	17 13 7	8·73	2·78	1·82	1 54	15 1	16 33	3·30	−0·51	−0·22
18 14 1	23 11	14 50	10 1	N. 0 30	10 46	9·50	18 13 45	9·50	1·92	2·64	1 12	14 57	15 46	3·25	−0·31	+0·04
19 14 33	23 53	14 40	10 3	N. 5 35	11 7	10·14	19 14 17	10·14	2·44	2·44	1 30	15 47	15 54	3·45	−0·22	−0·45
20 15 5	0 36	14 29	10 4	N. 10 23	11 28	9·90	20 14 49	9·90	1·97	2·50	1 17	16 6	15 30	3·19	+0·13	−0·17
21 15 34	1 19	14 15	10 2	N. 14 33	11 48	9·91	21 15 18	9·91	1·73	2·37	1 13	16 31	15 12	2·94	−0·40	−0·64
22 16 6	2 4	14 2	9 11	N. 18 14	N. 12 8	9·06	22 15 50	9·06	1·15	2·24	0 55	16 45	14 41	2·52	−0·96	+0·02
23 16 38	2 50	13 48	9 7	N. 21 5	12 29	11·33	22 16 22	11·33	0·71	1·71	0 45	17 7	14 17	1·85	−0·82	−0·33
24 17 9	3 38	13 31	9 0	N. 22 55	12 48	11·62	23 16 53	11·62	1·02	1·09	1 26	18 19	14 41	1·49	+0·79	−0·44
25 17 42	4 28	13 14	8 1	N. 23 45	13 8	11·82	25 17 26	11·82	0·34	0·64	0 56	18 22	13 54	0·73	−0·72	−0·38
26 18 26	5 18	13 8	7 2	N. 23 24	13 28	11·30	26 18 10	11·30	0·79	+0·27	2 22	20 32	15 14	0·83	+0·42	+0·04
27 19 18	6 8	13 10	6 6	N. 21 51	13 47	12·24	27 19 2	12·24	0·66	−0·80	4 41	23 43	17 35	1·04	−0·86	−0·50
28 20 34	6 58	13 36	6 1	N. 19 7	14 6	10·23	28 20 18	10·23	2·07	−0·40	3 22	23 40	16 42	2·10	+0·82	+0·02

The purport of the deductions from these computations will be more distinctly seen on taking the means for each eighth part of the lunation. This operation, which required for the means the subdivision of each 7 days period into two equal parts of $3\frac{1}{2}$ days each, was thus performed:—The mean of days 1, 2, 3 was taken, and the mean of days 1, 2, 3, 4 was taken, and the mean of these two means was adopted as the fitting mean for the first subdivision of $3\frac{1}{2}$ days. Then the means of days 4, 5, 6, 7 and of days 5, 6, 7 were taken, and their mean was adopted as mean for the second subdivision of $3\frac{1}{2}$ days.

MEANS, for Subdivisions each one-eighth part of Lunation, of the Principal Elements for Positions of Sun and Moon, London Tides, and Malta Tides.

Subdivision.	London Tides.				Position of Sun and Moon.		Malta Semidiurnal Tides.						Malta Diurnal Tides.	
	London Retard of High Water on Moon's Transit.	London Retard diminished by 14h 3m.	London Tide Half Range.	London Tide Half Range diminished by 9 ft. 1 in.	Moon's Declination.	Sun's Declination.	Malta Mean Height.	Malta Mean Height diminished by 9·33 in.	Malta Retard of High Water on Moon's Transit.	Malta Retard diminished by 16h 4m.	Malta Tide, Half Range.	Malta Tide Half Range diminished by 2·39 in.	Value of p.	Value of q.
	h. m.	h. m.	ft. in.	ft. in.	° ′	° ′	inches.	inches.	h. m.	h. m.	inches.	inches.	inches.	inches.
I.	14 41	+0 38	7 10	−1 3	N. 15 50	N. 4 45	10·18	+0·85	17 20	+1 16	3·03	+0·64	+0·01	−0·25
II.	14 22	+0 19	11 0	+1 11	S. 2 25	6 17	8·94	−0·39	15 56	−0 8	3·54	+1·15	+0·92	+0·50
III.	13 30	−0 33	10 9	+1 8	S. 19 30	7 37	7·54	−1·79	15 47	−0 17	1·72	−0·67	+0·34	+0·43
IV.	13 31	−0 32	7 6	−1 7	S. 21 17	8 53	7·33	−2·00	16 59	+0 55	1·45	−0·94	−0·17	+0·12
V.	14 50	+0 47	8 11	−0 2	S. 5 52	10 10	8·62	−0·71	16 24	+0 20	3·10	+0·71	−0·34	−0·16
VI.	14 31	+0 28	10 3	+1 2	N. 8 58	11 22	9·92	+0·59	15 34	−0 30	3·20	+0·81	−0·18	−0·37
VII.	13 43	−0 20	9 4	+0 3	N. 21 8	12 34	10·82	+1·49	14 27	−1 37	1·80	−0·59	−0·38	−0·27
VIII.	13 18	−0 45	6 10	−2 3	N. 21 45	13 41	11·33	+2·00	16 8	+0 4	1·25	−1·14	+0·02	−0·21
No. of Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14

Section V.—*Examination of the Tidal Results for Malta obtained in the last Section.*

The first result claiming attention is that for the daily mean heights of the water abstracted in columns 7 and 8, column 8 giving the difference of the value for each eighth part of lunation from the mean of all. And the numbers in column 8 are to be compared with those in column 5 for the moon's declination. There cannot be a doubt that they exhibit an accurate luni-menstrual variation of height, depending on the moon's declination. Viewing the extreme slowness of the formation of this inequality, I think it probable that the amount at Malta is very little smaller than that on the Atlantic coasts of Spain and Morocco, and that its epoch is very little in retard, and that thus we have gained a term in the expression for the ocean-tides which it might not have been easy to obtain from direct observation.

The second result is that for the retard of high water on moon's transit in column 9; the difference of each number from the mean of all, in column 10, shows the semi-menstrual inequality of time at Malta, which is perfectly well defined. On comparing it with the tabular semi-menstrual inequality of time at London, in column 2, it appears that its amount is nearly the same as that at London (at first sight it appears larger, but that is perhaps the effect of small irregularities), and its epoch is certainly about three days earlier than the tabular epoch for London. How far the London retardation may depend on friction (which was shown in the treatise on Tides and Waves in the 'Encyclopædia Metropolitana' to be the probable cause of the "age of tide") I am unable to say.

The mean retard of semi-menstrual tide on the moon's transit appears to be about $16^h\ 4^m$, which may be taken as the "Establishment" of Malta.

The third result is that for the semi-range in height of Malta tide in column 11, and its variations in column 12. And here again is a perfectly clear semi-menstrual inequality. This is to be compared with the tabular London semi-menstrual inequality in column 4. In regard to the proportion of inequality of height to the whole semi-range in height, if we divide the sum of inequalities without regard of sign by the mean semi-range, the quotient for Malta is 2·78, while that for London is 1·13 (supposing that no error has been committed in regard to the zero of London heights). I cannot explain this difference. In regard to the epoch of inequality, the heights agree with the times in making the epoch for Malta about three days earlier than that for London.

It appears curious that such results should be obtained, apparently with certainty, in a single lunation from these miniature tides, in which the semi-range, even for spring tides, is less than a hand-breadth.

The remaining results relate to the diurnal tides, and these are not so clear as those which we have already treated. We may first consider what we ought to expect in diurnal tides. Referring everything to lunar time (not quite the same thing as tidal time) we should expect that the lunar diurnal tide would occur at the

same lunar hour every day, and with a coefficient periodical in a month. The solar diurnal tide, if sufficiently important to be considered, would have a coefficient varying slowly, and the epoch of its daily tide would advance on the moon's, gaining 2π in a month (approximately). So that putting M and S for certain coefficients depending on the moon and sun, the first nearly constant and the latter not varying much in the lunation, and R and r for certain angles, both periodical in a lunation (nearly), we should have for approximate height at any time—

$$\begin{aligned} &\text{M sin R cos (moon's hour angle} - \text{A)} \\ &+\text{S cos (sun's hour angle} - \text{A)}, \end{aligned}$$

$$\begin{aligned} &\text{or M sin R cos (moon's hour angle} - \text{A)} \\ &+\text{S cos (moon's hour angle} + r - \text{A)}, \end{aligned}$$

$$\begin{aligned} &\text{or (M sin R} + \text{S cos } r\text{) cos (moon's hour angle} - \text{A)} \\ &-\text{S sin } r \text{ sin (moon's hour angle} - \text{A)}. \end{aligned}$$

Each of the factors, it is to be remarked, is periodical in a lunation.

It will be remembered that p is the factor of the sine of tidal angle measured from the tidal zero of each day, and that q is the factor of the cosine of the same angle. Now if we connect the expression $p \sin\theta + q\cos\theta$ into the form B. cos $(\theta - \text{A})$, where θ is the tidal angle from the zero of tidal time, we obtain

	inch.	h.	m.
I.	$+0{\cdot}25 \cos(\theta -$	11	51),
II.	$+0{\cdot}90 \cos(\theta -$	3	45),
III.	$+0{\cdot}55 \cos(\theta -$	2	33),
IV.	$+0{\cdot}21 \cos(\theta -$	20	21),
V.	$+0{\cdot}38 \cos(\theta -$	16	19),
VI.	$+0{\cdot}41 \cos(\theta -$	13	44),
VII.	$+0{\cdot}47 \cos(\theta -$	15	38),
VIII.	$+0{\cdot}21 \cos(\theta -$	11	38).

And if instead of θ we introduce ϕ, the tidal angle from the moon's transit, where $\theta =$

ϕ—London retard of high water on moon's transit $+16^{\text{m}}$,

we obtain for the diurnal tide

	inch.	h.	m.	inch.	h.	m.
I.	$+0{\cdot}25 \cos(\phi -$	2	16)			
II.	$+0{\cdot}90 \cos(\phi -$	17	51)	$= -0{\cdot}90 \cos(\phi -$	5	51)
III.	$+0{\cdot}54 \cos(\phi -$	15	47)	$= -0{\cdot}54 \cos(\phi -$	3	47)
IV.	$+0{\cdot}21 \cos(\phi -$	9	36)	$= -0{\cdot}21 \cos(\phi -$	2	24)
V.	$+0{\cdot}38 \cos(\phi -$	6	53)			
VI.	$+0{\cdot}41 \cos(\phi -$	3	59)			
VII.	$+0{\cdot}46 \cos(\phi -$	5	5)			
VIII.	$+0{\cdot}21 \cos(\phi -$	0	40)			

Remarking the smallness of the tide (which is little more than a finger-nail's breadth) it may be considered that the tides II., III., IV. present that opposition of sign to VI., VII., VIII. which they ought to maintain, and that the term depending on S may explain some part of the remaining discordance.

There is one mechanical consideration applying to the register of the diurnal tide which does not apply in the same degree to the semidiurnal tide. A single sheet at a time, as I understand, was placed on the revolving barrel; and it is not easy to attach this without the risk of a little inclination, which would produce the appearance of a diurnal tide; and there was no base-line produced by a pencil on the fixed part of the instrument which would give evidence on this point. No error, however, appears to have been produced in the mean height for the day.

Section VI.—*On the "Seiches" or Non-Tidal Undulations of Short Period at Malta.*

I have mentioned above the fluctuations of short period observable on the tidal record made by the self-registering tide gauge, and the methods of eliminating their effect in the treatment of the tides. During the month of the tidal discussions these fluctuations are small, but in some following seasons of 1871 and 1872 they became more important.

Their general characteristic is; that they are simple harmonic curves (excepting in the larger undulations in 1872, when their heads are sometimes notched, as by the intermixture of small waves originating from different causes); that they recur with great but not perfect uniformity at intervals of about 21 minutes of time; and that they continue for many hours at a time, sometimes for entire days; that their magnitude is very variable, sometimes small, sometimes amounting to ± 6 inches (or producing a range of 12 inches), much exceeding that of the luni-solar tides.

These fluctuations, occurring in a sea usually so tranquil as regards movements of slow character, were naturally known at Malta, and were not unfrequently attributed (conjecturally) to volcanic disturbances of Stromboli. I knew, however, that similar fluctuations were recorded by a self-registering tide-gauge at Swansea (see the 'Encyclopædia Metropolitana,' "Tides and Waves"), and was persuaded that they were due to some hydrodynamic cause.

At this time I received from Dr. Forel, of Lausanne, an account of his remarkable investigations on the undulations locally known as "Seiches," in the Lake of Geneva, and on similar but less conspicuous fluctuations in other lakes of Switzerland. ('Annales de Chimie et de Physique,' 5^{me} serie, tom. ix., 1876; 'Archives des Sciences de la Bibliothèque Universelle,' August and December, 1876; May, 1877.) On comparing the fluctuations on the tidal sheets with the descriptions by Dr. Forel, and above all with his engraved diagrams, it was impossible to doubt that they are phenomena of the same class. Every form delineated by Dr. Forel is to be found, I believe, upon the Malta sheets; but I think that the simple harmonic curve of

longest period occurs more frequently at Malta than in Switzerland. The origin assigned by Dr. FOREL is, I think, most certain; that they are waves originally caused by winds; but that they are reflected from one side and another of the limited sea, and thus become stationary waves. The waves forming the seiches of Malta are reflected, I suppose, from the shores of Sicily and Africa.

On examining the chart of those seas, it appears that a large bank, covered by comparatively shallow water, projects from the African coast, bounded roughly by a line nearly from Cape Bon to the island Linosa; and that between that bank and a narrower bank on the Sicilian side there is a broad sea-channel of approximately uniform width and of extremely deep water. I imagine that the reflection of undulations takes place principally, not at the shores of the land, but at the edges of the banks bounding the deep water. I have not yet ventured on a numerical calculation, but in rough estimate it appears to me that the breadth and depth of this sea would hydrodynamically explain the return of waves at periods of 21^{m}. Such waves, once created, would be propagated to regions of the sea somewhat beyond those in which they are formed.

For closing this account, I think that nothing more is required than to append a table descriptive of the seiches on the days in which they are large enough to attract attention. I have thought it sufficient to state the number of undulations occurring in a group between two limits of time, thus giving the average length in time of an undulation, and to state the greatest elevation or depression measured from the luni-solar tidal curve which occurs in the group. The limits of the groups are quite arbitrary, having been determined in most instances for convenience by the length of the sheets of paper on which the measures were transcribed.

From—	To—	Interval in Time.	Number of Waves.	Mean Duration of One Wave.	Largest Rise or Fall in the Group.
d. h. m.	d. h. m.	h. m.		m.	inches.
1872. June 9 6 10	1872. June 9 13 15	6 55	18	23	2·2
13 15	20 45	7 30	20	22·5	1·7
20 45	10 4 10	7 25	19	23·4	6·4
10 4 10	12 10	8 0	20	24	5·0
12 10	20 15	8 5	19	25·5	6·8
20 15	11 4 10	7 55	20	23·75	7·8
11 5 20	10 15	4 55	14	21·1	8·2
10 15	17 10	6 55	19	21·8	4·2
17 10	21 10	4 0	12	20	2·1
21 20	12 1 20	4 0	12	20	2·8
28 0 5	28 6 55	6 50	18	22·8	1·5
6 55	14 35	7 40	20	23	0·9
14 35	20 15	5 40	19	17·9	0·9
20 15	29 0 45	4 30	12	22·5	1·5
29 22 10	23 45	1 35	4	23·8	1·2
30 0 5	30 4 10	4 5	10	24·5	1·8
4 10	11 45	7 35	19	23·9	3·0
11 45	19 0	7 15	20	21·75	3·2
19 0	July 1 3 15	8 15	19	26·1	1·8
July 1 3 15	11 10	7 55	19	25	1·6
11 10	18 40	7 30	19	23·7	1·7
18 40	20 55	2 15	6	22·5	1·2
6 5 10	6 9 30	4 20	13	20	1·2
9 30	17 0	7 30	19	23·7	1·9
17 0	21 25	4 25	12	22·1	2·2
21 40	23 50	2 10	6	21·7	2·4
7 0 10	7 6 30	6 20	16	23·75	4·7
30 0 10	30 8 35	8 25	18	28·1	1·0
8 35	18 50	10 15	19	32·4	1·3
19 10	20 30	1 20	3	26·7	0·8
August 28 21 30	August 29 5 45	8 15	20	24·75	2·4
29 5 45	13 15	7 30	19	23·7	4·5
13 15	15 10	1 55	5	23	4·5

Appendix.

My first knowledge of the Seiches at Swansea was derived from a letter of J. W. G. Gutch, Esq., dated "Swansea, Feb. 18, 1838," of which the following is an extract:—

"I have some very singular curves marked [by the self-registering tide-gauge] in last month, and should much like to hear your explanation of them. They appear thus [with a rough diagram], and generally the irregularities occur at the top of the tide, and apparently at intervals of about a quarter of an hour or twenty minutes; they seem to be large tidal waves."

In my reply, dated February 27, 1838, I said: "The small irregularities of height which you mention puzzle me extremely. I do not see how they can come from the tides; whether from any strange reflections of waves in the bay or across the channel I cannot tell."—G. B. Airy, *October* 4, 1877.

VII.—*Report on the Total Solar Eclipse of April 6, 1875.*

By J. N. Lockyer, *F.R.S., and* Arthur Schuster, *Ph.D., F.R.A.S.*

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[Plates 9–14.]

I. INTRODUCTORY.

It is never an easy task to make out the plan of operations for the observation of a phenomenon so rare and of such short duration as a total solar eclipse. We must be careful on the one hand not to risk failure by the adoption of new and uncertain methods, and on the other hand we must bear in mind that the mere repetition of what has been done before does not justify any large expenditure of time and money.

In drawing out the instructions for the expedition the Committee of the Royal Society had to consider in how far the old methods could be perfected, and in how far new ones should be tried.

The principal methods hitherto employed successfully in total solar eclipses consist in spectroscopic eye observations and the obtainment of photographs of the corona. As the Royal Society had secured the services of Professor Tacchini, and as Mr. Janssen intended to observe the eclipse for the French Government, it was considered that spectroscopic eye observations were sufficiently provided for. As far as the photographic impressions of the corona itself were concerned, it was arranged that the same instrument with which Colonel Tennant had taken his photographs during the Eclipse of 1871 should be sent to one of the stations with an observer practised in its use.

Considering, therefore, that the attack of the corona was in excellent hands as far as the old methods were concerned, the Committee of the Royal Society decided to adopt new methods which should open fresh fields of research.

We give a short account of what these methods were and what questions they are likely to solve.

The Prismatic Camera.

During the Total Solar Eclipse of 1871 Mr. Respighi and Mr. Lockyer independently made observations with a spectroscope deprived of its collimator. A series of rings was seen by them corresponding to the refrangibilities of the rays sent out by the corona. The chief object of the observers during the last eclipse was to

obtain photographs of these rings, and the instrument employed has been termed a *prismatic camera*.

The great advantage of the prismatic camera is that it combines the functions of a telescope with those of a spectroscope, that is to say, it does not present us with the spectroscopic view of one section only of the corona, but of the whole chromosphere and corona. The instrument which was in use in Siam consisted of a camera of 5 feet focal length. The object glass, which belonged to Mr. LOCKYER, had an aperture of $3\frac{3}{4}$ inches. In front of the object glass was placed a prism with a refracting angle of about 8 degrees.

Supposing that the corona and chromosphere only send out the same homogeneous light, one image only will appear on the sensitive plate, the only effect of the prism being to displace the image. As far as protuberances are concerned we know they give a spectrum of bright lines, and we expect therefore to find on the plate each protuberance represented as many times as it contains lines in the photographic region. The different protuberances would be arranged in a circle round the sun, and these circles would overlap or not, according to the dispersive power of the prism and the difference in refrangibility of the lines. Fig. 1, Plate 9, represents a series of protuberances such as we might expect to find if the dispersive power is small. Fig. 2, Plate 9, the same protuberances if the dispersive power is large. The dotted line represents the edge of the sun. As far as the corona is concerned we know very little. If the conclusion which TENNANT and STONE derived from recent eclipse observations is correct, and the higher regions of the corona send out continuous light, we shall find no distinct outline of the corona as we do in ordinary photographs, but we shall find this image drawn out along the line of dispersion.

Thus a corona which would appear in an ordinary photograph as fig. 3 will be drawn out as represented in fig. 4. Such an image would present a striated appearance, each irregularity being drawn out by the prism. If such an irregularity were confined on an ordinary photograph to a mathematical point it would appear in the plates exposed in the prismatic camera as a mathematical line. As a rule, however, the irregularity will cover a surface of measurable extent. The visibility of such a local irregularity depends on the relative brightness of the surrounding objects, which will overlap, and, if bright enough, mask the irregularity. The continuous spectrum will be most easily observed, if, as actually happens, it is confined to the lower part of the corona. The moon in this case will form a sharp edge to the irregularity, and prevent any overlapping from the side on which it is situated. If the corona give a series of bright lines instead of the continuous spectrum we shall find a series of outlines on the photograph similar to that corresponding to the protuberances. We might indeed have the two cases combined, and then we should find a series of images standing out of the continuous band. If we find that part of the corona gives a continuous spectrum that part alone will be drawn out into a band. We thus see that the prismatic camera not only gives us an indication of the spectrum

of one part only of the corona, but that it gives us a combined representation of the spectrum of every part of the corona and chromosphere, and that careful examination of the result enables us to analyse it into its constituents.

The Spectroscopic Camera.

The chief drawback of the prismatic camera consists in the difficulty of obtaining a scale by means of which the refrangibility of the different rays can be determined. In order to complete the preparations as much as possible, it was arranged to endeavour to obtain photographs of the spectrum of the prominences by means of a telescope and ordinary spectroscope, the slit of which was provided with shutters, so that the solar spectrum could be photographed and used as a scale either before or after totality. It was hoped that photographic impressions of at least the brightest lines of the chromosphere could be obtained and identified by means of the solar spectrum. These brightest lines could then have been easily recognised on the plates of the prismatic camera, and would have formed a scale for the weaker protuberance lines and other phenomena visible on the plates.

Before discussing in detail the results, we have to give a short account of the journey and the preparations.

II. CHOICE OF STATIONS.

Three stations were available for the observation of the eclipse. The eastern coast of the Malayan Peninsula (Siam), the western coast of the Malayan Peninsula, and the Nicobar Islands. As the weather was rather doubtful during the month of April at all three stations, it was decided to divide the expedition into three parts. Although the journey to Siam was much longer, and much less time was therefore left for preparations on the spot, the liberal invitation and offer of help by the King of Siam, made it certain that all possible preparations would be made before the arrival of the expedition. Circumstances over which the expedition had no control prevented them from carrying out the original plan of sending some of the observers to Mergui, on the western side of the Malayan Peninsula. There were observers therefore at two stations only; Lem Chulie, in the Malayan Peninsula, and Camorta, in the Nicobar Islands.

III. THE EXPEDITION TO SIAM.

Journey to the Observatory.—Preparations for the Eclipse.

The expedition left Southampton on February the 11th, in the Peninsular and Oriental Steamship 'Surat.' It consisted of the following gentlemen:—

Mr. Arthur Schuster.
Mr. R. Meldola.
Mr. Frank Edward Lott.
Mr. Frederick Beasley.
Mr. J. Reynolds.

They were joined at Suez by Dr. H. W. Vogel, of Berlin.

At Galle Messrs. Meldola, Reynolds, and Dr. Vogel separated from the rest, and waited for the Government steamer which should carry them to Camorta.

The remainder of the party arrived in Singapore 24 hours late, and at once communicated with the Governor of the Straits Settlement, in order to avoid any possible delays in the journey. Sir Andrew Clarke placed H.M.S. 'Lapwing' at the disposal of the expedition, but he could not tell when the steamer would be able to start. As the Siamese merchant steamer 'Kromahtah' left Singapore the same night for Bangkok, the expedition took Sir Andrew Clarke's advice to take a passage in this boat, especially as it was urged that she would complete the passage in less time than the 'Lapwing.'

Dr. Schuster, however, forwarded a request to Sir Andrew Clarke to send the 'Lapwing' as soon as she was ready to the spot of observation, so that the expedition might profit by the help of the officers and crew. The expedition has also to acknowledge the assistance they have received by the valuable advice of the Honourable Major McNair, a gentleman who is well acquainted with the country of Siam.

The S.S. 'Kromahtah' arrived in front of the bar which prevents the entrance into the Meinam river at low water at noon, on Sunday, the 28th March. A slight accident to the engine had caused a delay of several hours, in consequence of which the steamer could not enter the river before nightfall. It was late in the night when the expedition at last arrived at Bangkok, after a journey of 45 days. In spite of the inconvenient hour, two boats were, by order of His Majesty the King of Siam, on the look out for the expedition to convey them to the residence of Mr. Alabaster.

It was past one o'clock in the morning when they arrived there, but several important points were settled during the night in order to secure a speedy journey to the observatory, which, under the superintendence of Captain Loftus, had been already built on the spot suggested by the Committee of the Royal Society. It became, however, apparent next morning that it was impossible to leave on that day. Several important points had to be settled with the Siamese authorities, the instruments had to be transhipped, and owing to the state of tide it was useless to leave after eleven o'clock in the morning. Much to their regret the expedition were compelled to defer their departure until Tuesday morning. The day, however, was not lost. The observatory had been built on a lonely spot on the sea coast, and the expedition was, therefore, entirely dependent for any help on the capital. Arrangements were made for regular communications with the capital.

We cannot speak too highly of the assistance which the expedition has derived from the intelligent aid of Mr. ALABASTER. His thorough acquaintance with the objects of the expedition, aided by his knowledge of the language and high position in the country, had enabled him to make many arrangements before their arrival which saved a great deal of time, and, in fact, rendered the completion of the preparations in the short time left before the eclipse possible. The expedition called on His Excellency CHAU PHYA SRI SURAWONGSE WAY WADHN-KALAHOME (the Minister of War), His Excellency CHAU PHYA BHANUWONGSE KROMATAH (the Minister of Foreign Affairs), and His Excellency PHYA BASHAKARAWONGSE (Private Secretary to His Majesty the King). One of the chief reasons which had induced Dr. SCHUSTER to pass the day in Bangkok was to call on the English Consulate, with the request to send on, with as little delay as possible, the much-needed aid from the gunboat, which was hourly expected. The expedition was chiefly in want of intelligent workmen. In case any instrument had been damaged on the journey they were without resources to remedy the fault. The expedition was kindly received by Mr. NEWMAN, the Acting Consul, who promised to do everything in his power to further the objects of the expedition.

In the afternoon the expedition had an audience with the King. His Majesty expressed the great interest which he took in the objects of the expedition. He referred to the well known great knowledge of astronomy which his father possessed. The late King had died in consequence of a fever contracted on a journey made to observe the total solar eclipse which had taken place in 1868 in the southern parts of his kingdom. Finally His Majesty said that he had given orders that every possible help should be given to the expedition.

Early on the next morning the expedition embarked on the Siamese S.S. 'The Northern Siam Enjoying,' which had been placed at their disposal. An unfortunate delay on the journey prevented them from reaching the observatory that night, and they had to anchor near the coast in a very rough sea. On the morning of Wednesday, at 10 o'clock, they at last arrived at the observatory. The ship had to anchor about half a mile from shore. At the observatory Captain LOFTUS had been engaged for some time to prepare for the arrival of the expedition. The spot had been judiciously chosen. A small brook ran into the sea close by. A landing stage had been erected in the brook. A channel had been marked out in the sea through which the boats which were to carry the instruments could enter the brook. The landing of the instruments was, therefore, greatly facilitated; but the strong wind and rough sea prevented any attempt to effect the landing during the first day.

The place of the observatory, as determined by Captain LOFTUS, was latitude 13° 0′ 30″ N., and longitude 100° 2′ 10″ E., being about 1½ miles S.W. of the central line. The longitude had been obtained by means of a magnetic bearing, which could be obtained from the top of a tree on a distant pagoda marked on the Admiralty Chart.

It had taken considerable time and trouble to clear the ground from the jungle by

which it was covered. A comfortable house had been built of bamboo sticks and palm leaves for the English observers; a similar house was built for Mr. J. Janssen, who had arrived at the observatory about a week before the English expedition.

His Grace the ex-Regent of Siam arrived at the observatory on the following day, and stopped until after the eclipse. He took a great interest in the preparations, and his presence was a guarantee that no trouble should be spared to render the stay of the King's guests as pleasant as possible. The minor arrangements, which were considerable, had been entrusted by the King to the Governor of Pitchaburee, to whose anxious care to carry out all their wishes the expedition is greatly indebted.

It must be borne in mind that everything had to be brought through considerable distance either by water or over bad roads, and the continued wants at short notice of wooden planks, bricks, &c., often severely taxed the energies of the Siamese officials. Even the drinking water had to be brought from a spot many miles distant.

All through Wednesday the wind did not abate, and arrangements were made to land the instruments during the night if possible. At three o'clock in the morning Mr. Lott went on board, and succeeded after some difficulty, and not without risk, in getting the instruments into the small boats. The boats had to make several journeys, but all went well, and on Thursday, the 1st of April, at noon, all the instruments were at the observatory. The eclipse was to take place on the following Tuesday. This late arrival was due to several unforeseen events. Our delay between Galle and Singapore, and slow passage to Bangkok, and a double considerable delay on both sides of the Meinam bar, all combined to produce a total delay of three or four days. Until the arrival of part of the crew of the 'Lapwing,' on the evening of the 3rd of April, we were without the help of trained workmen. Though the instruments were fairly in order during the eclipse, there is no doubt that the short time of the preparations has considerably damaged the results.

Everything belonging to the photographic department was put under the supervision of Mr. Beasley. Captain Loftus had prepared several dark rooms, two of which were on wheels and could be shifted to any spot where they were wanted. The walls of the rooms were made of several layers of palm leaves, but these were not found a sufficient protection against sunlight. As the expedition had brought tents, they were put up inside the dark rooms prepared by the Siamese. This arrangement proved to be of very great advantage. While the photographer could work in complete darkness inside his tent, the chemicals were placed within easy reach on shelves in the outer room, to which only very little light had access. The assistants carrying the plates to and from the instruments could enter the room and communicate with the photographer without allowing any light to enter the tent.

The instruments had suffered some damage on the journey which could not be repaired without proper tools. The workmen from the 'Lapwing' were, therefore, somewhat impatiently expected.

On the evening of the 1st of April a steamer was announced to be in sight, but, to

the disappointment of the observers, it only brought a letter from Sir WILLIAM WISEMAN, Commander of the 'Lapwing,' announcing that he had arrived at Bangkok, and asking in what way he could assist the expedition. Owing to the great readiness with which the Siamese facilitated communication with the capital, the long-expected help from the 'Lapwing' arrived at last on Saturday night, the 3rd of April. During the two remaining days those of the officers and crew which Sir WILLIAM WISEMAN had sent did everything in their power to assist the expedition, and contributed not a little to the successful completion of the preparations.

The erection of the siderostat gave comparatively little trouble; owing to the excellent packing of Messrs. COOKE, it was lifted out of the case almost ready for use. A brick foundation had been built for it, and the adjustments were made in the usual way. The beam of rays reflected from the mirror were thrown into a telescope lent to the expedition by Mr. LOCKYER. The telescope was placed inside a hut so as to protect it from showers of rain. A movable cover could be placed over the siderostat. The image given by the telescope was focussed on the slit of a spectroscope which was provided with quartz lenses and prisms.

We cannot help mentioning here the great advantages which the siderostat possesses over the equatorial in temporary observatories. It is always comparatively easy to find a sure foundation for the plate on which the siderostat rests, while it is much more difficult firmly to fix the pillar of the equatorial into the ground. The horizontal telescope belonging to the siderostat can be easily levelled and firmly fixed with brick and mortar. In latitudes, moreover, where the sun stands high at noon, solar observations with a refracting equatorial are very inconvenient.

The steamer which had carried the officers of the 'Lapwing' also had brought Mr. ESCHKE, assistant to Mr. VOGEL, who had been on one of the expeditions sent out to observe the transit of Venus, and had come to Bangkok in the hope of finding Professor H. W. VOGEL, who, as we have already mentioned, was attached to that part of the expedition which had proceeded to the Nicobar Islands. As, however, the expedition was greatly in want of another gentleman skilled in photography his arrival proved fortunate. The coating and development of the plates could now be altogether separated and carried on in two separate rooms, which helped to prevent confusion during the eclipse. The spectroscopes were adjusted in the usual way. Photographs of distant objects were taken, and when the camera had been in this way adjusted for almost parallel rays the prisms were set into minimum deviation for the violet rays, and the collimators adjusted so as to send parallel rays through the prisms. One of the collimators was found to be too long for accurate adjustment. As it could not be shortened easily, and as the wooden camera was easily made shorter, the latter plan was preferred to bring out the FRAUNHOFER lines. We confess that this was an unfortunate mistake, as converging rays passed in this way through the prism. It must, however, be remembered that part of the day only preceding the eclipse could be entirely given up to the adjustment of the spectroscopes, and that owing to the

many and various considerations which had to be attended to, mistakes were almost inevitable.

His Majesty the King of Siam had offered to send FRANCIS CHIT, a skilled photographer in his service, to assist the members of the expedition. As Mr. BEASLEY had brought with him a small but exceedingly good camera for landscape photographs, Dr. SCHUSTER thought it advisable to try to get photographs of the corona. Although the camera did not follow the sun's motion, it was hoped that in short exposures this motion would not much affect the results. Mr. FRANCIS CHIT was charged with the preparation and development of the plates.

If any of the instrumental adjustments were not made with the accuracy which would have been desirable, it was not through want of care of any member of the expedition.

It was only by working 12 hours a day in the hottest month of the year, and sometimes during additional hours of the night to adjust the clocks, that the instruments were in working order a few hours before the beginning of the eclipse.

After this introduction it will be useful to give a short account of the final arrangements which were made for observation.

IV. ARRANGEMENTS DURING TOTALITY.

The observatory which, as has already been mentioned, was built before our arrival, consisted of two parts, separated from each other by a distance of about 40 yards. The smaller of the observatories was intended for the siderostat. Mr. LOTT was put in charge of it during totality. It was hoped that photographs of the spectrum of the prominences and lower parts of the corona should be obtained by the set of instruments connected with the siderostat.

The larger observatory was bounded on each side by a dark room. In one of these rooms Mr. ESCHKE prepared the plates. In the other Mr. BEASLEY took charge of the development. The sailors of the 'Lapwing' had been trained to carry the photographic plates at the times fixed beforehand to and from the instruments.

Attached to Mr. PENROSE'S equatorial was a spectroscope with a camera which was of shorter focal length than the one connected with the siderostat. The equatorial carried the prismatic camera. Arrangements were made to change the plate one and three minutes after the beginning of totality, so as to obtain three photographs of the different phases of the eclipse.

Mr. and Mrs. LOFTUS took charge of the small camera, by means of which a set of photographs of the corona were obtained. The times of exposure were fixed at the suggestion of Mr. JANSSEN at 2, 4, 8, and 16 seconds. A double set of four photographs was thus obtained. Mr. CHIT in a separate dark room prepared and developed the necessary plates. The Honorable H. N. SHORE, R.N., had undertaken

to take a sketch of the corona. Messrs. A. W. Murray and Pattison called out the time remaining for observation.

The following gentlemen also gave their valuable assistance during the eclipse :—

Messrs. W. J. Firks, R.N., Bietje, W. Bray Hendricks, Edward Loftus ; also Captain A. J. Thompson, S.R.N., and Captain Chung, S.R.N., and Mom Dang.

V. THE ECLIPSE—GENERAL APPEARANCES.

Description of eclipses by eye-witnesses are generally so discordant that no conclusion can be drawn from them. The following remarks, however, seem worthy of notice :—

A great many of the inhabitants of Bangkok were fortunate enough to witness the total solar eclipse in 1868, and they were unanimous in their opinion about the great difference in the appearance of the corona and in the general aspect of the eclipse. The difference seems to have been so striking that some of the Siamese asserted that this last one was no total eclipse at all. The first point they mentioned was the much greater darkness in 1868. In proof of this we cite the following from an account of the eclipse by Sir Harry St. George Ord, C.B., then Governor of the Straits Settlement, who witnessed the eclipse at the invitation of the late King of Siam.

"At the time of the complete obscuration of the sun, which took place at $11^h\ 30^m$, the darkness was so considerable that at a distance of a few feet a person's features were undiscernible and all sense of distance appeared to be lost, the thermometers could not be read without a light held close to them, and the face of the sky was studded with stars as in deep twilight."

During this last eclipse several persons both at the observatory and in Bangkok were looking out for stars, and more than four could in no case be seen. Though the lamps had been lighted for the benefit of those who had to draw, write, or read, the lamps were blown out by the wind, but no inconvenience whatever was produced by this.

The signal for beginning and end of totality could be seen without difficulty at the small observatory 40 yards off, and Mr. Lott could read a small watch hung up a distance of $1\frac{1}{2}$ feet from his face inside a shed which did not admit any direct light from the corona. Part of this striking difference between the two eclipses may be due to the peculiar atmospheric conditions. There was, indeed, in 1875 a considerable haze over the country, and the sky, though cloudless, was by no means clear. But eye-witnesses affirm that it is the corona itself which was brighter this time and much better defined. The light in the former eclipse was much softer and pleasant to look at. In the last one it was quite as intense as a bright full moon.

Another difference which those who could compare this eclipse with the one in 1868 noticed related to the corona, which they agreed was much more irregular and

less well defined than on the present occasion. The characteristic feature of the eclipse in 1868 was formed by the protuberances, and the corona fell more into the background. This time the protuberances could only be seen with the naked eye by a few, and the corona surrounded the moon like a regular and well-defined star.

Some observers note the particular appearance of one protuberance, which they say was of a white dazzling light, and stood out bright from the background, while the other protuberance appeared red and dark on a bright ground. On referring to our photographs we find that the white protuberance was indeed by far the strongest, and contained a great quantity of the particular ultra-violet light, of which we shall have to speak in discussing the results of the prismatic camera.

VI. RESULTS OF THE PRISMATIC CAMERA.

The plates exposed in the prismatic camera present at first sight a somewhat complicated appearance. Two plates have been exposed during totality. No. 1 (fig. 9, Plate 10) during one minute, and No. 2 (fig. 8, Plate 10) during two minutes. They show only such differences as are to be attributed to a difference in phase of the eclipse.

As the protuberances must form the scale to which we shall have to refer the rest, they are the first object of our investigation.

1. *Protuberances.*

During the first part of the eclipse two strong protuberances close together are noticed*; on the limb towards the end these are partially covered, while a series of protuberances came out at the other edge. The strongest of these protuberances are repeated three times, an effect of course of the prism, and we shall have to decide if possible the wave lengths corresponding to the images. We expect *à priori* to find the hydrogen lines represented. We know three photographic hydrogen lines: F, a line near G, and h. F is just at the limit of the photographic part of the spectrum, and we find indeed images of protuberances towards the less refrangible part at the limit of photographic effect. For, as we shall show, a continuous spectrum in the lower parts of the corona has been recorded, and the extent of this continuous spectrum gives us an idea of the part of the spectrum in which each protuberance line is placed. We are justified in assuming, therefore, as a preliminary hypothesis, that the least refrangible line in the protuberance shown on the photograph is due to F, and we shall find support of this view in the other lines. In order to determine the position of the next line the dispersive power of the prism was investigated. The prism was placed on a goniometer table in minimum deviation for F, and the angular distance between F and the hydrogen line near G, i.e. $H\gamma$, was found, as a mean of several measurements to be 3′. The goniometer was graduated to 15″,

* Figs. 5 and 6 show the protuberances as seen on the photographs at the beginning and end of eclipse.

and owing to the small dispersive power, and therefore relatively great breadth of the slit, the measurement can only be regarded as a first approximation. Turning now again to our photographs, and calculating the angular distance between the first and second ring of protuberances, we find that distance to be 3′ 15″. We conclude, therefore, that this second ring is due to hydrogen. We, therefore, naturally looked for the third photographic hydrogen line, which is generally called h, but we found no protuberance on our photographs corresponding to that wave length. Although this line is always weaker than Hγ, its absence on the photograph is rather surprising, if it be not due to the fact that the line is one which only comes out at a high temperature. This is rendered likely by the researches of FRANKLAND and LOCKYER (Proc. Roy. Soc., vol. xvii. p. 453).

We now turn to the last and strongest series of protuberances shown on our photographs. The distance between this series and the one we have found reason for identifying with Hγ is very little greater than that between Hβ and Hγ. Assuming the distances equal, we conclude that the squares of the inverse wave lengths of the three series are in arithmetical progression. This is true as a first approximation. We then calculated the wave length of this unknown line, and found it to be approximately somewhat smaller than 3957 tenth-metres. No great reliance can be placed of course on the number, but it appears that the line must be close to the end of the visible spectrum.

In order to decide if possible what this line is due to, we endeavoured to find out both by photography and fluorescence whether hydrogen possesses a line in that part of the spectrum. We have not at present come to any definite conclusion. In vacuum tubes prepared by GEISSLER containing hydrogen a strong line more refrangible than H is seen, but these same tubes show between Hγ and Hδ other lines known not to belong to hydrogen, and the origin of the ultra-violet line is therefore difficult to make out. We have taken the spark in hydrogen at atmospheric pressures, as impurities are easier to eliminate, but a continuous spectrum extends over the violet and part of the ultra-violet, and prevents any observation as to lines. We are going on with experiments to settle this point.

Should it turn out that the line is not due to hydrogen, the question will arise what substance it is due to. It is a remarkable fact that the calculated wave length comes very close to H. YOUNG has found that these calcium lines are always reversed in the penumbra and immediate neighbourhood of every important sunspot, and calcium must therefore go up high into the chromosphere. We draw attention to this coincidence, but our photographs do not allow us to draw any certain conclusions.

At any rate it seems made out by our photographs that the photographic light of the protuberances is in great part due to an ultra-violet line which does not certainly belong to hydrogen. The protuberances as photographed by this ultra-violet ray seem to go up higher than the hydrogen protuberances, but this may be due to the relative greater length of the line.

In some of the protuberances the lower edge does not seem to touch the body of the moon, but the gas seems to hang like clouds in the corona.

Figs. 8 and 9, Plate 10, are copies of the photographs obtained by means of the prismatic camera.

2. *The Corona.*

We shall now have to examine the corona as shown on the photographs taken by the prismatic camera. If the spectrum given by the light of the corona is a line spectrum, we expect to find well-defined edges forming the limb of the moon. Only one such edge is seen on the photograph. It corresponds to the second ring of protuberances, and is, therefore, probably due to hydrogen. This was to be expected, as we know by the eye observations of LOCKYER and RESPIGHI that the hydrogen lines are the strongest lines in the photographic part of the corona. The upper part of the corona, as seen on the photographs, is such as would be given by homogeneous light, *i.e.* only one image of the corona is seen. We have tried several ways of finding the wave length of this light. A circle of the size of the image of the moon was cut out of paper and put over the photograph until the corona was symmetrical round this circle, as we know it to have been symmetrical round the moon. When the circle was in this position its edge coincided with the $H\gamma$ lower edge of the corona.

The photograph of the corona was enlarged to the same size as the photograph of the prismatic camera. They were laid over each other so that the outlines of the corona coincided as well as possible. Here, again, it was found that the edge of the moon coincided with the $H\gamma$ ring of protuberances.

We think, therefore, that we are entitled to say that the photographic rays of the corona are chiefly due to the hydrogen line $H\gamma$. Fig. 7, Plate 9, represents the protuberances and image of the corona symmetrical about the second series of protuberance as seen on our photograph.

In addition to this line spectrum of the corona, our photographs show strong marks of a continuous spectrum in its lower regions. This is chiefly shown by the well-defined structure running parallel to the line of dispersion due to irregularities drawn out by the prism into bands. We can easily determine the limits of the continuous spectrum by examining them at the inner side of the photographs. On the one side the structure stops short at the hydrogen line F. On the other edge, however, it extends to a considerable distance beyond the ultra-violet prominence line. Traces of light are distinctly seen to a wave length of 3530 and beyond.

Knowing the limits of the continuous spectrum we can determine approximately the height to which it extends; the distance between the extreme limit of the structure to the protuberance near H is about one and a half times the distance between the protuberance F and H. We know that we have no photographic trace beyond F, hence the angular height of the protuberance must be at least half the angular distance between the two prominences. The angular distance between the two pro-

minences is rather more than 6′, hence the continuous spectrum extends at least to a distance of 3′ from the sun. The continuous spectrum is well shown on the photographs, figs. 8 and 9, taken at the beginning and end of the eclipse respectively. One of the plates in the prismatic camera was exposed during the last part of the eclipse until the signal for the end of totality was given. All the observers agreed in saying that the signal was given rather too late, and the fogginess of the plate indicates the great intensity of the light. Yet the edge of the sun is not drawn out into a continuous band, but rather into three distinct bands, showing that at the time of exposure the lower part of the chromosphere only had appeared. These lower parts gave out light of such intensity that to all observers it appeared as if the body of the sun had come out.

A series of rapid photographs taken at beginning and end of totality would no doubt give most interesting results.

VII. RESULTS OF THE SPECTROSCOPIC CAMERA.

Arrangements were made to photograph the spectrum of the prominences and corona by means of a camera attached to a spectroscope. No results were obtained, and we must, therefore, discuss the reason of this failure, and see whether the instruments can be improved in such a way as to give a fair chance of success in other eclipses. The light of the corona no doubt is very feeble, but considering that the prismatic camera has given good photographs in one minute, and that we have obtained direct photographs of the corona in two seconds, success is not out of question. Even the instruments used during the last eclipse have not had a fair trial. Owing to delays on the journey only one day could be given to the adjustments of the instruments, and as the spectroscopes had never been used before they could not in that time be brought into the best possible state. It was, indeed, found that all the collimators were too long. As they could not be made shorter without considerable delay, the cameras had to be adjusted for the rays which were converging as they passed through the prism. This, of course, damaged much the definition of the image, especially as the prisms were made of quartz. In order to obtain a reference spectrum the cusp of the reappearing sun was thrown on the slit and exposed for about 15 seconds. Yet even this reference spectrum did not appear, showing that the instrument must have been out of order. The focal length of one of the cameras used was too large, yet the other ought to have given results had the image of the corona been bright enough. This camera was attached with its spectroscope to the only equatorial available for use for the purpose; it was kindly lent to the expedition by Mr. Penrose. The proportion of the aperture to the focal length in this instrument is 1 : 16. This proportion in the reflecting telescope used by Dr. Janssen is 1 : 4, it has, therefore, 16 times as much light as that used by the English expedition. The observations to be made during total solar eclipses have arrived at such a point that a successful attack

can only be made with instruments constructed for the purpose. We feel sure that if in future expeditions an instrument similar to that used by Mr. JANSSEN is provided, the spectrum of the corona can be photographed. As far as the higher regions are concerned, it is true we shall not learn anything beyond what is given by the prismatic camera, but as far as the lower regions are concerned important results may be expected.

VIII. PHOTOGRAPHS AND SKETCHES OF THE CORONA.

We must inquire next what information was obtained from the photographs and sketches of the corona itself. Eight photographs were obtained by means of a small camera belonging to Mr. BEASLEY, the object glass having a focal length of about 13 inches. The camera was not moved by clockwork, but during the short exposure the sun's movement, though visible, does not materially affect the results. The times of exposure were 2, 4, 8, and 16 seconds, and two photographs of each exposure were obtained. As these two sets show exactly the same phenomena we need only consider one set, remembering, however, that the other set excludes the possibility of any of the results being affected by irregularities in the collodion-film. The four photographs are shown in figs. 10, 11, 12, and 13.

Looking over one set we are first struck by the rapid increase in the extent of the corona through an increase in the time of exposure; the last of the photographs, having been exposed 16 seconds, shows an extent exceeding the diameter of the sun.

The next point of interest is the symmetry of the outer corona round the sun's axis. This symmetry was dwelt on by Mr. E. J. STONE, in the eclipse of April, 1874. (Memoirs of Royal Ast. Soc., vol. xlii. p. 31.)

The small size of our photographs does not, indeed, allow us to fix the position of the axis within one or two degrees, but even then, allowing for this uncertainty, the symmetry is very striking. We have marked, as well as could be ascertained, the position of the sun's axis on fig. 7, Plate 9. The similarity in the corona, as observed by us and by Mr. STONE just one year before, is exceedingly curious. The drawings given by Mr. STONE, in so far as they agree amongst themselves, agree with the corona observed at Siam. This similarity does not merely extend to the symmetry about the sun's axis, but also to the irregularities in this symmetry. Thus the nearly straight boundary lines of the corona, which cut the axis at nearly right angles, are not quite parallel but converge in both eclipses towards the east. The west side of the corona seems much more compact, the east side broken up into what the Siamese called fish-tails. The similarity is, perhaps, most striking between Mr. BRIGHT'S drawing (L. C., p. 51) of the corona in 1874, and the drawing made by Prince TONG (fig. 14, Plate 13), by order of His Majesty the King of Siam, of the corona in 1875. The two drawings could certainly pass for representations of one and the same eclipse.

At the observatory the Honorable H. N. SHORE undertook to sketch the corona.

Fig. 15 is the sketch made by him during totality. Fig. 16 a more detailed copy directly after totality.

The similarity between this sketch and Mr. WRIGHT's of the corona in April, 1874, again is very striking.

One point connected with Mr. SHORE's drawing deserves special notice. A remarkable rift in the corona towards the south excited his notice during the eclipse, and he tried to give as correct a representation of it as possible. This rift is shown not only in all our photographs of the corona itself, but also in the prismatic camera. It is, indeed, the rift by means of which the upper part of the corona could be most exactly determined to be due to hydrogen.

This shows that though the substance giving the green line may play an important part in the corona, the structure is in great part due to hydrogen.

This is confirmed by an observation of Captain HERSCHEL's, who, in 1871, found the green line of the corona to cross the field with the slit across the edge of a rift. (Memoirs of Royal Ast. Soc., p. 23.)

A great number of drawings have been made by the Siamese. We especially note the drawings made by the following gentlemen :—

H.R.H. CHAU FA MAHA MALA (fig. 17, Plate 14).
H.R.H. Prince DEVANNDAYWONGSE (fig. 18, Plate 14).
H.R.H. Prince CHETOCHEREUN (fig. 19, Plate 13).

His Majesty the King has sent a drawing of the prominences as seen by him during the eclipse (fig. 20, Plate 14).

IX. THE CAMORTA EXPEDITION.

It has already been stated that Mr. MELDOLA and Dr. VOGEL separated at Galle in order to join the expedition sent out from India in charge of Captain WATERHOUSE. They arrived at Camorta on the 22nd of March, and found that considerable preparations had already been made by the Assistant Commissioner, Mr. F. A. DE ROEPSTORFF. All the instruments were in excellent working order on the day of the eclipse, but clouds prevented any observation during totality.

Dr. VOGEL, assisted by Mr. GOOD, third officer of H.M.S. 'Enterprise,' had intended to photograph the spectrum of the prominences by means of plates prepared by his method, which had the greatest sensibility in the yellow part of the spectrum.

The prismatic camera was in charge of Mr. R. WOOD, chief engineer of H.M.S. 'Enterprise.'

The quartz telespectroscope was attended to by Mr. MELDOLA.

Arrangements had been made to make polariscopic observations by means of a polariscopic camera, placed at the services of the expedition by Mr. SPOTTISWOODE, F.R.S. The instrument was attended to by Dr. RUD. The dark chamber was in charge of Mr. REYNOLDS.

Captain WATERHOUSE had intended to photograph the corona by means of the same instrument used by Colonel TENNANT in 1871.

Captain KING and Mr. CHATTERJEE had volunteered to act as timekeepers.

Professor TACCHINI undertook all the observations to fix the latitude and longitude of the spot of observation, and also to determine the local time. Professor TACCHINI had also watched any prominences during the days preceding the eclipse and on the morning of the eclipse. He writes: "On the mornings of the 4th and 6th April the sun was almost entirely free from protuberances, which was in favour of the special object of the expedition to examine the light of the corona. On the morning of the 6th at the angle 107° I saw bright flames which seemed to indicate an eruption, but after having finished the examination of the limb all had disappeared, and with the narrow slit I saw no reversed lines beyond the ordinary ones of hydrogen, and I also obtained the same result in other parts of the limb."

Considering the complete state of preparation, it is a matter of great regret that the observations were prevented by the state of the weather.

X. SUMMARY OF RESULTS.

In conclusion we give a summary of the results which we have obtained:—

1. The light given out by the prominences when analysed by a prism gives in the less refrangible part of the photographic spectrum two lines, which are most likely due to the hydrogen lines $H\beta$ and $H\gamma$.

2. The strongest protuberance line lies in the ultra-violet. The actinic effect of the protuberances must chiefly be due to this line.

3. The upper parts of the corona give a photographic spectrum which is homogeneous and apparently due to the hydrogen line near G.

4. The lower parts of the corona send out a strong continuous spectrum, extending into the ultra-violet to a wave length 3530, that is, beyond N, and reaching to a height of about 3′ from the sun.

5. Photographs of the corona show that the extent of the corona rapidly increases with increasing times of exposure. The corona has, therefore, no definite outline.

6. We have been able to confirm the results obtained by Mr. STONE that the corona is symmetrical round the axis, the greatest extent being in the direction of the sun's equator.

7. The corona presents a striking resemblance to that observed just one year before by Mr. STONE at the Cape of Good Hope.

VIII. *Experimental Researches on the Electric Discharge with the Chloride of Silver Battery.**

By WARREN DE LA RUE, *M.A., D.C.L., F.R.S., and* HUGO W. MÜLLER, *Ph.D., F.R.S.*

Received April 10,—Read May 16, 1878.

[PLATES 15–18.]

PART II.—THE DISCHARGE IN EXHAUSTED TUBES.

WE cannot flatter ourselves that we have done more during our three-and-a-half years' work than contribute a few facts towards the data necessary for the solution of the problem, "What is the cause of the beautiful phenomenon of stratification produced by electric discharges in vacuum tubes?" which, having been first noticed by M. ABRIA in 1843, was independently re-observed by Mr. (now Sir WILLIAM) GROVE in 1852,†

* These researches have been prosecuted independently and without the knowledge of much that has been done by other workers in the same field. Subsequently to the communication of this memoir we have diligently searched the papers of other physicists, and have extracted from them many interesting passages which, by permission of the Council of the Royal Society, we have added in the form of foot-notes at various parts of the paper. As it is quite possible that some papers may have escaped our notice, a list of those consulted is given in the Appendix, note A.

MASCART, in his valuable 'Traité d'Electricité Statique,' t. ii., pp. 128–141, 1876, has given a succinct account of the phenomena of the discharge in vacuum tubes, and the various hypotheses which have been proposed to account for them.

† GASSIOT (Bakerian Lecture, Phil. Trans., 1858, pp. 1–16) gives the following history of the stratified discharge:—

"The striated condition of the electric discharge in vacuo which takes place when the terminal wires are inserted in a well exhausted receiver in which a small piece of phosphorus has been previously placed, was first announced by Mr. GROVE in his communication to the Royal Society, 7th January, 1852; his paper is printed in the first part of the Transactions for that year, and was subsequently published in the Phil. Mag., December, 1852, with a supplementary note, dated 9th June, wherein Mr. GROVE states 'that he found the transverse dark bands could be produced in other gases when much attenuated, probably in all.'

"The phenomena of stratification in the discharge in vacuo were subsequently observed in Paris by RUHMKORFF, who obtained the effect by using the vapour of alcohol; they were again noticed by MASSON, DU MONCEL, QUET, and other continental electricians, who all describe the *intense white light without stratification* produced in the barometrical vacuum."

It appears, however, that GROVE was anticipated by ABRIA (Ann. de Chim. vii., 1843, pp. 477–478), who, experimenting with the secondary current of an induction coil, obtained in air at a pressure of 2 m.m., in an exhausted receiver, a brush-discharge from the positive (a ball) which did not quite reach the

and has since engaged the attention of so many physicists. Our excellent and highly esteemed friend the late Mr. GASSIOT, working at first with an induction coil, but more recently on the same lines as ourselves (voltaic batteries of high potential *), has published results of great interest, many of which are confirmed by our own experience; while, on the other hand, we have enjoyed pleasurable intercourse and exchange of thought with our contemporary, Mr. W. SPOTTISWOODE, who is still pursuing with great acumen and originality a similar investigation, both with the induction coil and the HOLTZ machine, with which he has recently used condensers of great capacity, like those we employ and have described in Part I. If we arrive at the same results by different paths, the one investigation will support the other, and for each may be claimed more reliance than if unconfirmed.

Throughout our labours we have felt so strongly the necessity of obtaining numerical results as data for the foundation of a theory, that we have not hesitated to risk much in this cause. By the fusion of terminals, or the sudden discharge of the condenser, we have lost a vast number of very beautiful tubes; but gradually, by the adoption of various devices, and by the employment of instruments specially constructed and insulated to suit the high potentials we deal with, we have succeeded in overcoming the various impediments, so that we can now readily obtain values for the physical quantities that enter into consideration in our experiments.

There is a serious trouble connected with the study of the discharge in rarefied gases, for, after a very short time, the tubes completely and permanently change, so as no longer to present the splendid stratifications witnessed on a first trial. We believe these changes occur much more rapidly with the battery, in consequence of the greater amount of current, than with the induction coil; but the fact appears to be well known to Dr. GEISSLER, of Bonn, who, on the occasion of a visit to our laboratory, brought with him some tubes through which no current had previously passed (virgin tubes, as he calls them), which presented most beautiful phenomena lost for ever after too brief a period.

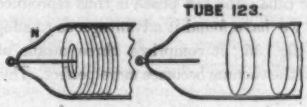
Tube 123 (Cyanogen), for example, when first connected with the battery, presented strata which completely filled the tube without leaving a dark space near the negative,

negative (a point), where there was a dark interval: he says, "De plus, cette flamme ou aigrette qui part du pôle positif présente notamment à sa partie supérieure (en supposant la pointe negative en haut) des zones alternativement obscures et lumineuses. Ces zones sont concaves vers la boule quand la pointe (negative) est rapprochée de cette dernière; elles deviennent convexes vers la boule lorsque la pointe en est très-écartée."

* Mr. GASSIOT made several batteries of different kinds in the course of his experiments; on the occasion of a visit to his laboratory, January 26, 1875, the current of his LECLANCHÉ battery was measured by us with a voltameter. The current of 1000 new cells was found to be 0·07464 W; that of the whole 3000 cells, 1000 of which had been a long time in use, 0·04718 W. Taking the LECLANCHÉ as 1·48 volt the internal resistance of the new battery must have been 19·83 ohms per cell; that of the whole 3000, 31·37 ohms per cell. The striking distance of the whole 3000 between a conical point and a disc 0·125 inch diameter was only 0·025 inch; whence the inference is that the insulation was, at that time, imperfect.

some threading themselves on it, as shown on the left of fig. 33; but after a few seconds the strata widened out as on the right-hand figure, then other changes occurred, and the first phases have never been reproduced.

Fig. 33.



Another case is presented by the nitrogen tube fig. 34, the right-hand figure showing the first phase, and the left-hand figure a second phase, which in its turn has for ever disappeared, and has been replaced by the ordinary disc-form of strata.

Fig. 34.

After spending much time in experiments with tubes prepared for us by Dr. GEISSLER, Messrs. ALVERGNIAT Frères, of Paris, and Mr. HICKS, of Hatton Garden, with the vexation of finding that we could not often enough repeat our experiments, we ultimately came to the conclusion to have others made, but not exhausted, and to perform ourselves the charging and exhaustion.* The tubes we usually employ have a glass stop-cock fitted to them at each end; they are 32 inches long, and from 1·75 to 2 inches in diameter; the terminals are of aluminium, and about 29 inches apart, one being a ring, the other a wire bent at a right angle, so as to point in the direction of the axis of the tube (see No. 144, fig. 37), for we have found that the phenomena vary according as the ring or wire is made positive. These we exhaust and fill with any gas we may wish to experiment with, and gradually exhaust again, noting the phenomena presented at different pressures, different potentials, and with different amounts of current. We re-fill and exhaust the tube again and again, and mostly obtain, under the same conditions, as nearly as possible the same phenomena, of which we are careful to make sketches and, if possible, to obtain photographic records.

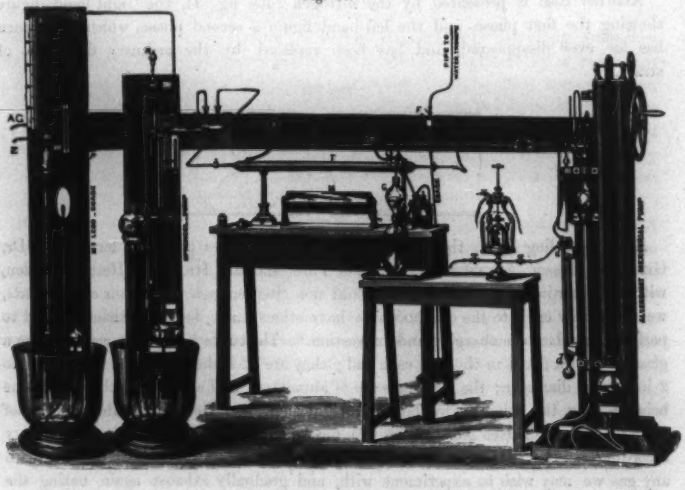
In some cases we make use of tubes provided with a calibrated chamber between two stop-cocks, as *a*—*b*, No. 145, fig. 37, the chamber in this particular case having $\frac{1}{1000}$th of the capacity of the tube. After a tube has been exhausted so as to

* GASSIOT was driven to the same conclusion; he says, in speaking of GEISSLER'S tubes: "I reluctantly laid them aside, and for all experiments I have to describe each tube was charged and exhausted by myself or in my presence."

produce a particular phase, and in the course of the experiment the exhaustion has been carried beyond that degree which permits of the production of that phase, one or more charges of gas may be successively admitted into the tube by filling the calibrated chamber with gas at any particular pressure, and then opening the stop-cock communicating with the tube; the lost phase is thus reproduced.

The apparatus which we have found it advantageous to adopt for the exhaustion of our tubes is shown in fig. 35; it comprises three means of exhaustion which are successively employed as the vacuum becomes more perfect. The first is an ALVERGNIAT

Fig. 35.



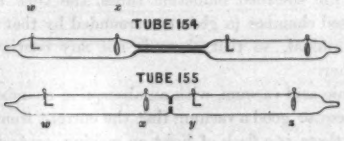
high-pressure water *trompe* in connexion with the high-pressure water-main of the West Middlesex Water Company, the head of water being 106 feet; it produces a vacuum to within half-an-inch (0·47 in. = 12 millims.) of the height of the barometer. The pipe leading to it is so marked in the drawing; it is attached, through a cock, to a four-way-junction-piece F, provided with three more cocks, communicating:— one to one end of the tube T, one to the last drying bottle of the gas generator G G, and one to a mercurial gauge. The other end of the vacuum tube T communicates by means of a Y-piece to both, an ALVERGNIAT mercurial pump, on the right of the figure, and a SPRENGEL pump, on the left. After the *trompe* has done its work, the ALVERGNIAT is used for rapid exhaustion, and then shut off by means of the glass cock C,

leaving the exhaustion to be completed by the SPRENGEL; we have thus obtained, by the *pumps alone*, in tubes 32 inches long and 2 inches in diameter, vacua of only 0·002 millimetre pressure, equal to 2·6 millionths of an atmosphere—a vacuum so perfect that the current of 8040 cells would not pass. The apparatus is in connexion with a MCLEOD gauge,* by means of which pressures to 0·00005 m.m. can be determined. Besides this gauge, the SPRENGEL and ALVERGNIAT pumps have their own gauges, which read to a millimetre. M is a rotating mirror consisting of a four-sided prism mounted on a horizontal axis and provided with a multiplying wheel; on each face of the prism is fastened a piece of looking-glass. The reflection of the tube in the mirror enables one to examine whether an apparently nebulous discharge consists really of strata, also whether and in what direction there is a flow of strata which may appear quite steady to the eye. The observations are facilitated by covering the tube with a half cylinder of cardboard having a slit in the direction of its axis about $\frac{1}{10}$ inch wide. R is a radiometer attached to the SPRENGEL; *d*, *d*, a drying tube containing sticks of potash used when gas is introduced from a reservoir through the ALVERGNIAT.

In fig. 37, to which is attached a scale of feet and inches to enable a judgment to be formed of their dimensions, tubes of various forms are represented. It will presently be seen that the resistances of these tubes bear no exact relation to the distance between the terminals, but that it is affected greatly by the bore of the tube; the small spectrum-analysis tubes, 83, 93, and 95, a portion of which has a capillary bore, offer generally great resistance to the battery current, while much longer tubes, 1 and 2, of larger bore, offer far less.

In order to test how much of this depends on the length of the constriction, we had made two tubes, 154 and 155, fig. 36, of nearly the same length, 16 inches, and internal

Fig. 36.



diameter $\frac{15}{100}$ths of an inch, the residual gas in each case being Carbonic acid, CO_2. The distances between the several terminals of tube 154 are respectively between *w*

* (Phil. Mag., Aug. 1874.) When the mercury cistern is raised, a portion of gas at the same pressure as that in the tube is shut off at *b*, and compressed in the small graduated chamber, *a*, at the top of the bulb, to different degrees, in our gauge, from $\frac{1}{4900}$ to $\frac{1}{19600}$, according as the gas is less or more rarefied; the mercury at the same time rises in the pressure column, *p*, and its height affords the means of determining the pressure of the gas in the tube. Tables have been prepared to give the value of the reading by inspection.

and x 4·375 inches, between x and y 5·75 inches, and between y and z 4·25 inches; the length of the constricted part being 3·75 inches, and its diameter 0·125 inch. The distances for tube 155 are respectively between w and x 5·25 inches, between x and y 2·375 inches, and between y and z 5·25 inches; the constricture in this case is a glass diaphragm 0·03 inch thick with a hole 0·125 inch in diameter.

The following results were obtained from observations made January 25th, 1878 :—

Terminal $z+$; terminal $w-$ (to Earth).

	Tube 154.	Tube 155.
Difference of potential between z and y	75	81
" " y " x (the constriction)	138	32
" " x " w	118	146
" " z " w	331	259

The diaphragm in tube 155 being 0·03 inch in thickness, and in tube 154 the constriction being 3·75 inches long, the one is 125 times longer than the other, but the ratio of the differences of potential between x and y in the two cases is only 4·31. It is evident, therefore, that the main effect is due to the simple constricture of the tube.

Among the tubes depicted in the diagram fig. 37, only the following require any special allusion being made to them in this place :—

Tube 145 has at the right hand a chamber for holding an absorbent substance (spongy palladium, charcoal); the vertical tube is for connexion with the pump, and the left hand small tube for connexion with the supply of gas; by using spongy palladium with hydrogen, a vacuum has been obtained in which 11,000 cells could not produce a current.*

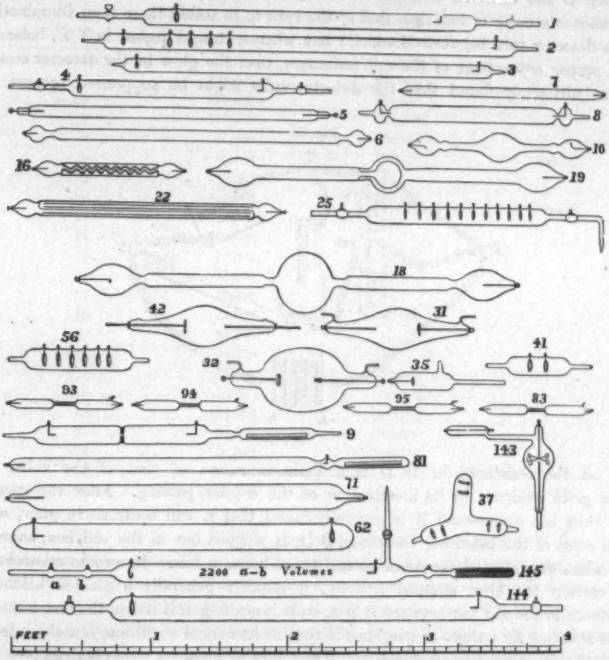
Tube 19 is one of the so-called induction tubes, the tube enclosing one of the wires ending in a closed chamber (a globe) surrounded by that portion of the tube enclosing the other terminal, so that there is not any continuous gas space from one terminal to the other.

Tube 81 has a carbonic acid vacuum, with an absorption chamber containing hydrate of potash, which produces so good a vacuum that the current from 11,000 cells will not pass continuously, but there is a flash of light on making contact in one direction but not in the other.

Tube 143 is a tube so thoroughly exhausted that a spark from an induction coil will not pass between two terminals only 0·1 of an inch apart, although of sufficient tension to jump across the wires outside the tube several inches distant; this communicates with a radiometer.

* Gassiot (Phil. Trans., 148–150) describes several "*non-conducting vacua*" produced by absorbing substances (caustic potash, and chloride of calcium).

Fig. 37.



The diagram, fig. 38, shows the arrangement by which, in our earlier experiments, we measured the resistance of a tube. The tell-tale tube* had to be substituted for the galvanometer in the ordinary WHEATSTONE bridge, as the difference of potential between C and D fluctuated greatly in the course of the experiment, causing violent swings of the needle.†

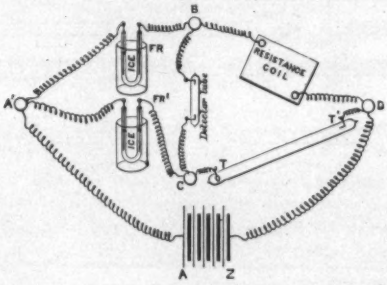
A Z is the battery, the A terminal of which is connected at A′, in the bridge arrangement, with two equal fluid resistance tubes, FR and FR′, of 420,000 ohms, placed in vessels containing ice, to keep them at a constant temperature; an adjustable coil resistance is inserted between B and D; the tube T T′, to be tested, is placed

* A tube selected for the readiness with which it permits the passage of a current of 440 cells.

† Proc. Roy. Soc., vol. xxiv. p. 167, 1876.

between D and C, the Z terminal of the battery being connected to D. When the resistance is greater or less than that of the tube to be tested there is an illumination in the detector tube between B and C; but when a current passes in T T', balanced by a proper adjustment of the coil resistance, then the glow in the detector ceases. It was ultimately found that the detector tube might be suppressed because, as

Fig. 38.



soon as the resistance in B D is a little in excess of that of the tube, the latter gives evidence by its illumination of the current passing. After the current in a tube has commenced it is generally found that it will continue to glow, even when some of the balancing resistance, B D, is plugged out in the coil box, showing that when once started the *working* resistance becomes less. If, on the other hand, the current has been stopped entirely, it requires generally a greater balancing resistance in the coil box between B D to start it again than it did in the first instance. After standing for a short or long time it regains its normal condition, but the interval required may amount to several days. The following numbers were obtained :—

Tube	Started with	Ran up to	Nature of the Gas.
1	200,000	250,000	
2	350,000	500,000	
3	400,000	(decreased)	
4	90,000	110,000	
5	170,000	290,000	
6	270,000	500,000	N
7	170,000	370,000	
8	50,000	60,000	
9	70,000	..	CO_2
10	150,000	..	
16	450,000	500,000	
18	62,000	..	
22	500,000	..	
25	50,000	80,000	
31	35,000	40,000	
32	37,000	..	
35	15,000	17,000	
37	54,000	..	
41	32,000	..	
42	15,000	70,000	N
56	40,000	45,000	
62	102,000	140,000	N
71	80,000	130,000	Cy
81	150,000	infinity.	CO_2
83	190,000	..	H
93	over 1,000,000	..	CO_2
94	700,000	..	I
95	700,000	1,000,000	$Si\ Fl_4$

Subsequently we found it to be more convenient not to make special determinations of the resistances of the tubes beforehand in the way just described, but to obtain them by reproducing the deflection of a galvanometer, or by measurements taken with an electrometer in the manner described in pp. 165–167, while observing the phenomena of stratification. We not only save time in this way, but obtain the resistance at the actual moment of the occurrence of any particular phase.

From measurements thus made with a tube having several wires about 1 inch apart (No. 25, fig. 37), or a SPOTTISWOODE tube* with a shifting terminal (No. 147, figs. 39 and 40), we found that the resistance of a vacuum tube, unlike that of a wire, does not increase in the ratio of the distance between the terminals for the same gas at the same pressure.†

* Recently, by permission of Mr. SPOTTISWOODE, we have had made tube No. 147, with the ingenious arrangement, suggested by his assistant Mr. P. WARD, of a movable terminal, attached to a spiral of fine copper wire, which permits of its being brought into actual contact with the opposite terminal, or placed at any required distance from it; this tube is marked out into eight equal spaces by slips of paper pasted outside.

† HITTORF (Pogg. Ann. CXXXVI., 1869, pp. 1–31 and 197–234) devised several experiments to show that

Fig. 39.

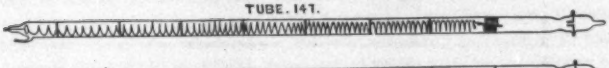


Fig. 40.

Tube 25 (CO_2) with 12 rings (not 11 as in fig. 37) 1 inch apart and 1200 cells.

	Between terminals.						
Numbers	1 to 3	1 to 4	1 to 6	1 to 7	1 to 8	1 to 9	1 to 10
Relative distances	1	1·533	2·667	3·267	3·867	4·533	5·198
Relative resistances	1	1·035	1·109	1·109	1·274	1·368	1·417

Spottiswoode tube (No. 147, CO_2) and 3240 cells.

	Between the terminals at various distances from 7 to 49 inches.						
Relative distances	1	1·86	2·71	3·57	4·43	5·29	6·14	7·00
Relative resistances	1	1·24	1·24	1·49	1·35	1·63	1·78	2·10

Thus, for five times the distance the resistance, the mean of 1–9 and 1–10, is in tube 25 only 1·43, and in tube 147, 1·54; for seven times the distance the resistance is in tube 147, 2·1. The degree of exhaustion of these two tubes is not known, but the internal pressure is, probably, less than 1 millimetre.

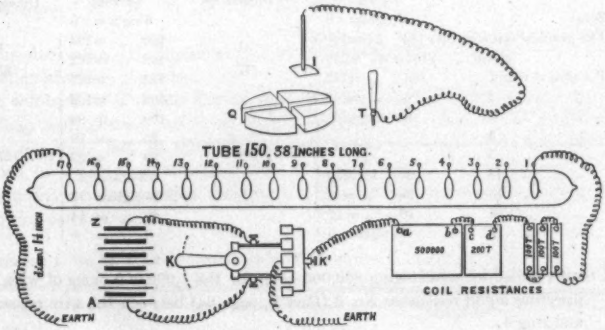
In making these experiments it was noticed that the resistance for equal distances appeared to be greater in proximity with the negative pole than in other parts of the tube, and fresh experiments were in consequence undertaken to ascertain the potential at the several rings by means of a delicate Thomson-Becker quadrant electrometer furnished with an induction plate, I, fig. 41, which may be adjusted to any required distance from the quadrant beneath it. The tubes employed among others were No. 25, described above, and two other longer tubes, namely, No. 149 (CO_2) with 12 rings 2 inches apart, and No. 150 (CO_2) with 17 rings also 2 inches distant. The current was led through a metallic resistance to the first ring, the last ring and the other pole of the battery being to earth. It was found that the greatest difference of potential occurs between the last ring and the last but one on the negative side, the next greatest difference being between the last and the last but

the influence of distance between the terminals varied according to the degree of rarefaction. For instance, he joined, side by side, two similar tubes, in which the distances between the terminals were relatively 12 : 1, and exhausted them together. The two terminals of the one tube were connected respectively to the two terminals of the other, and a galvanometer could be thrown into the circuit of either tube. He found that at notable pressures the discharge was exclusively across the smaller space: but at 0·5 m.m. his galvanometer did not show any difference in the currents which traversed the two tubes. Schulitz (Pogg. Ann. cxxxv., 1868, pp. 249–260) states that about that pressure which requires least difference of potential to produce discharge, the influence of distance between the electrodes is such that this difference of potential varies nearly in direct proportion to this distance; but when rarefaction is carried beyond that point, and the difference of potential necessary to produce discharge rapidly increases, the influence of distance between electrodes rapidly becomes inappreciable.

one on the positive side, but the difference in the former case is far greater than in the latter; in some cases there is little or no difference in the last but one and the last but two on the negative side; in these cases the last but one on the negative side was dark,* while all the others had a luminosity about them. The difference of potential between the rest of the rings is sensibly uniform.

The following observations, made December 21st, 1877, with tube 150, may be taken as an illustration of the method of measurement adopted. Batteries 6 and 7 (2400 rod cells) were employed, and adjustable resistances were inserted in circuit for the double purpose of affording the means of readily varying the strength of current without interruption, and of enabling a measurement of that current to be made with the electrometer. The connexions are shown in the diagram, fig. 41.

Fig. 41.



The circuit was first broken by removing the earth wire from ring 17, and the plug T, in connexion with the induction plate I, being touched at any point between K′ and ring 1 gave the reading for "Full Potential, open circuit;" next, the earth wire was replaced at ring 17, and the value for "Full Potential, closed circuit," was obtained by causing T to touch at K′. As these batteries had but small internal resistance, the difference between these two readings was scarcely perceptible. By touching T at rings 1, 2, &c., in succession, their potentials were

* An example of the dark space at conductors near the negative is shown at fig. 6, Plate 17. The dark spaces in a vacuum tube are regarded by De la Rive ('Comptes Rendus,' lvi., 1863, pp. 672–673) as offering less obstruction to the discharge than the bright layers. He inserted in the tube discs of metal connected to wires passing through its walls; these wires were connected to a galvanometer while the discharge was taking place: the derived current was found to be much less in the dark than in the bright portions of the discharge.

observed. The current was then reversed and similar observations were made. Next, for the purpose of making a better examination of the tube in detail, the induction plate I was lowered to that distance which gave as large a deflection for the difference of potential between the two ends of the tube as was convenient. After the potentials of the several rings had been measured in succession with both currents, the induction plate was restored to its original position, and one or two of the first observations were repeated for confirmation. The current was then varied by altering the resistance in circuit,* and fresh measurements made in the same order. Thus the following values were obtained :—

I. Circuit :—2400 rod-cells, 1 megohm resistance, tube 150. Induction plate at 2 inches distance from the quadrant.

	Current +	Differences.	Current −	Differences.
Zero	6 right= 0		6 right= 0	
Full potential (open circuit)	154 left=160	1	200 „ =194	2
(closed „)	153 or 4 „ =159	47	198 „ =192	65
Potential at ring 1	106 „ =112		133 „ =127	
„ „ 2	96 „ =102		108 „ =102	
„ „ 3	not observed		100 „ = 94	
„ „ 4	„		95 „ = 89	
„ „ 5	„	112	89 „ = 83	127
„ „ 14	26 left=32		not observed	
„ „ 15	20 „ =26		25 right= 19	
„ „ 16	16 „ =22		20 „ = 14	
„ „ 17	6 right= 0		6 „ = 0	

II. Circuit varied by substituting 800,000 ohms for the 1,000,000 ohms of wire, and inserting liquid resistance No. 3 (Part I., page 64) between the wire resistance and ring 1.

	Current +		
	1st Observation.	2nd Observation.	Mean Differences.
Zero	5 right= 0	5 right= 0	
Full potential (open circuit)	159 left=164	159 left=164	1
„ (closed „)	159 or 8 „ =163	158 „ =163	19·5
Potential after 800,000 ohms	139 „ =144	138 „ =143	27
„ at ring 1	112 right=117	111 „ =116	
„ „ 2	not observed	103 „ =108	
„ „ 3	„	97 „ =102	
„ „ 4	„	90 „ = 95	116·5
„ „ 15	„	25 „ = 30	
„ „ 16	„	18 „ = 23	
„ „ 17	5 right= 0	5 right= 0	

* This method of varying the current is arranged to save time. The circuit must not be interrupted in the course of a set of observations.

	Current— 1st Observation.	2nd Observation.	Mean Differences.
Zero	5 right= 0	5 right= 0	
Full potential (open circuit)	194 „ =189	192 „ =187	1
„ (closed „)	193 „ =188	191 „ =186	
Potential after 800,000 ohms	166 „ =161	167 „ =162	25·5
„ at ring 1	138 „ =133	136 „ =131	132
„ „ 17	5 „ = 0	5 „ = 0	

III. THE induction plate was lowered from 2 inches to 1½ inches. Current—. (The current+ was not observed for want of time.)

Ring	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Readings	276	217	200	187	174	159	144	130	116	104	90	76	62	48	35	22	0
Differences	59	17	13	13	15	15	14	14	12	14	14	14	14	13	13	22	

The observation III. illustrates that which has already been said concerning the fall of potential within the tube.

It will be noticed in case I. that there was a greater difference between the scale readings with positive and with negative currents than that which would result from the mere fact of the different poles being to earth. This was caused by torsion in the suspension arising from an imperfection in the arrangement of the instrument not at that time discovered. This does not, however, sensibly affect the following deductions :—

In case I. we have for the currents in Webers—

$$C+=\frac{\frac{47}{160}\times 2400\times 1{\cdot}03}{1{,}000{,}000}=0{\cdot}0007261, \text{ and } C-=\frac{\frac{65}{194}\times 2400\times 1{\cdot}03}{1{,}000{,}000}=0{\cdot}0008281,$$

and for the difference of potential in volts (V) between the two ends of the tube—

$$(C+)\ V=\tfrac{113}{160}\times 2400\times 1{\cdot}03=1730, \text{ and } (C-)\ V=\tfrac{127}{194}\times 2400\times 1{\cdot}03=1618.$$

These differences of potential would be reproduced if for the tube were substituted metallic resistances in ohms (R)—

$$(C+)\ R=\tfrac{113}{47}\times 1{,}000{,}000=2{,}383{,}000, \text{ and } (C-)\ R=\tfrac{127}{65}\times 1{,}000{,}000=1{,}954{,}000.$$

In case II.—

$$C+=\frac{\frac{19{\cdot}5}{164}\times 2400\times 1{\cdot}03}{800{,}000}=0{\cdot}0003674, \text{ and } C-=\frac{\frac{25{\cdot}5}{188}\times 2400\times 1{\cdot}03}{800{,}000}=0{\cdot}0004190.$$

$$(C+)V=\tfrac{116{\cdot}5}{164}\times 2400\times 1{\cdot}03=1756, \text{ and } (C-)V=\tfrac{133}{188}\times 2400\times 1{\cdot}03=1736.$$

$$(C+)R=\tfrac{116{\cdot}5}{19{\cdot}5}\times 800{,}000=4{,}780{,}000, \text{ and } (C-)R=\tfrac{159}{25{\cdot}5}\times 800{,}000=4{,}142{,}000.$$

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Selecting the observations with the current positive in each case and placing these in juxtaposition thus—

	C	V	R
Case I.	0·0007261	1730	2,383,000
„ II.	0·0003674	1756	4,780,000

we see that when C is varied in the ratio of 2 : 1, V remains sensibly constant, R varying as 1 : 2; that is to say, though the current is halved the difference of potential between the ends of the tube remains constant—a condition which could only be brought about when metallic resistance is substituted for the tube, by doubling this resistance.

This points to the important conclusion that *other things being kept constant* and the current alone varied, we should find the value of V *strictly* constant for all values of C; but it may readily be imagined that in experiments with 'vacuum tubes' it is not easy to ensure perfect constancy of the accompanying circumstances.

To test this conclusion we extended the range of our observations by varying the value of C as much as from 1 to 135. We give below the original measurements themselves, not the mean results, in order that the discrepancies in the readings obtained for V when C was kept as constant as our powers of control permitted, may be compared with the variations, such as they are, in the values of V when the circuit was purposely varied so as to produce currents of different strengths. These observations show clearly that discharge through rarefied gases cannot be at all analogous to conduction through metals; for a wire having a given difference of potential between its ends can permit one—and only one—current to pass; whereas, we see from the following measurements that with a given difference of potential between the terminals of a given vacuum tube, currents of strengths varying from 1 to 135 can flow. We are therefore led to the conclusion that the discharge in a vacuum tube does not differ essentially from that in air and other gases at ordinary atmospheric pressures—that it is, in fact, a disruptive discharge.*

Fig. 42.

Tube 31

* See Appendix, note B.

RESULTS of observations with tube 31 (fig. 42), CO_2, January 17–18, 1878.

	Circuit.	Observation.	C.	V.
I.	2400 cells, tube 31, 1,000,000 ohms (wire), a certain liquid resistance	*a*	182	
		b	156	533
		c	184	552
		d	207	511
		e		552
II.	„ „ „ less „ „	*a*	349	497
		b	349	511
		c		511
III.	„ „ „ „ „ „ „	*a*	539	380
		b		475
		c	454	521
		d	481	
IV.	„ „ „ „ „ „ „	*a*	1,568	478
		b	1,463	429
		c	1,536	416
		d	1,536	468
		e		442
V.	„ „ „ „ No „ „	*a*	1,998	460
		b		381
		c	2,053	409
VI.	„ „ 600,000 „	*a*	3,208	416
		b	3,089	412
		c	3,199	421
VII.	„ „ 400,000 „	*a*	3,964	400
		b	4,139	445
VIII.	„ „ 200,000 „	*a*	8,584	458
		b	8,584	424
IX.	„ „ 100,000 „	*a*	14,900	428
		b	15,390	466
		c	15,360	450
X.	1200 „ 20,000 „	*a*	24,030	435
		b	23,910	449

RESULTS of observations with tube 150 (page 165, fig. 41), January 28, 1878.

Circuit.			C.	V.
3600 cells	50,000 ohms and tube 150		2,300	413
,,	150,000 ,, ,,		1,260	386
,,	300,000 ,, ,,		787	367
,,	400,000 ,, ,,		625	370
,,	500,000 ,, ,,		518	360
,,	600,000 ,, ,,		435	367
,,	700,000 ,, ,,		374	367
,,	800,000 ,, ,,		331	366
,,	900,000 ,, ,,		291	373
,,	1,000,000 ,, ,,		267	365
,,	,, ,, ,,		269	373
,,	,, ,, ,,		266	369
,,	,, ,, ,,	and liquid resistance	208	352
,,	,, ,, ,,	more ,,	40	505
,,	,, ,, ,,	,, ,,	43	497
,,	,, ,, ,,	,, ,,	50	439
,,	,, ,, ,,	,, ,,	31	482
,,	,, ,, ,,	,, ,,	35	465
,,	,, ,, ,,	,, ,,	17	357

The results for tube 31 are given in microwebers (millionths of a weber) and volts: those for tube 150 are left in terms of the electrometer.

By fixing small rings of tinfoil to the glass near the places where the metal terminals are fused into the tube and connecting these rings to earth, we were able to cut off the leakage over the surface (which, in spite of precautions, is considerable,) and prevent it from interfering with our measurements of the potential of the gas *inside* the tube. The condition of the *outside* of the tube appears to have been the subject of much investigation by other observers: our experience points to the absolute necessity of cutting off leakage in order to obtain correct information concerning induced charges on the outside of the tube.

In a paper published in 1870 (Proc. Roy. Soc. vol. xix. p. 237), Mr. C. F. VARLEY stated: "The following laws were found to govern the passage of the current:—1st, each "tube requires a certain potential to leap across; 2nd, a passage for the current having "been once established a lower potential is sufficient to continue the current; 3rd, "if the minimum potential, which will maintain a current through the tube, be P, and "the power be varied to P+1, P+2, &c. to P+n, the current will vary in strength, "as 1, 2, &c. n. . . . It thus appears that a certain amount of power is necessary to "spring across the vacuum; after that it behaves as an ordinary conductor, excluding "that portion of the battery whose potential is P, and which is used to balance "the opposition of the tube."

Laws 1 and 2 are confirmed by our daily experience, but the experiments which then led Mr. VARLEY to the conclusion that, with a certain reservation, a "vacuum

tube" behaves as an ordinary conductor, lend themselves as additional proof of the constancy of the difference of the potentials of the terminals of the tube. The essential part of Mr. VARLEY's arrangement being a battery, of internal resistance r, joined by a resistance R to one terminal of a tube, the other terminal of which is connected to the other pole of the battery, then if $P+n$ be the difference of potential produced by the battery, and P the constant difference of potential between the terminals of the tube, the current must vary as $\frac{(P+n)-P}{R+r}$ or, if R be kept constant and large enough to render variations in r negligible, C varies as n.

From these results recently obtained, it follows that what, in the following account of experiments of earlier date, is termed the "resistance of a tube," must not be considered as analogous to metallic resistance: it indicates merely that the difference of potential between the terminals of the tube was the same as that between the ends of a wire of the given resistance when substituted for the tube in the particular circuit.

THE HISTORY OF SOME TUBES.

No. 129, *Hydrogen.*

We now give an account of the very great variety of phenomena presented by the same tube charged with hydrogen, No. 129, under different conditions of exhaustion when used in connexion with batteries of various potentials, and traversed by currents of different strengths.

This tube is 32 inches long and 1·6 inch in diameter, the terminals are a bent wire and a ring, about 1 inch in diameter, both of aluminium; it is furnished with a glass stop-cock at each end as represented in fig. 37, No. 144. The glass stop-cocks are connected with the mercurial pumps (ALVERGNIAT and SPRENGEL) and with the gas generator respectively, as shown in fig. 35.

During the course of the experiments about to be described several casualties occurred to the tube; for example, the partial fusion and distortion, first of the ring, then of the bent wire terminal; and by an accident the glass cocks were broken off and reattached. Notwithstanding these accidents, the same phenomena were again and again obtained under like conditions.

The experiments with 129 were commenced on July 1, 1876; great precautions were taken to thoroughly rinse out the air by completely exhausting the tube and filling it with dry hydrogen several times. The hydrogen was obtained by the solution of very pure rod zinc, like that used for the batteries, in diluted pure sulphuric acid in the proportion of 1 part of acid to 10 of water. It was dried by pumice moistened with sulphuric acid, and then with rods of hydrate of potash.

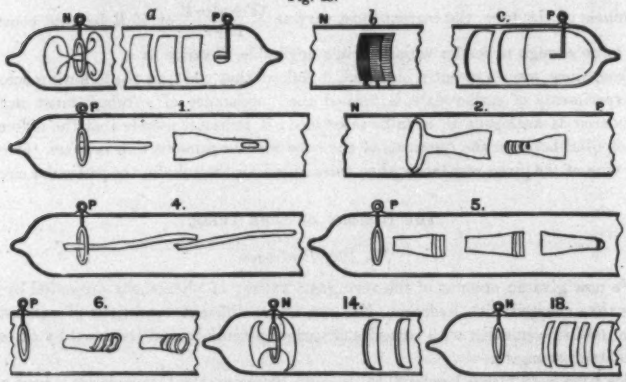
Tube 129, 1*st Charge of Hydrogen.*

Experiment 1.—Pressure 2 m.m. (millimetres), 2632 M (millionths of an atmo-

sphere), 2400 rod cells, (C.*) 0·014210 W. Discharge agitated, the strata about 0·5 inch apart.

2.—Pressure 1·2 m.m., 1579 M, 2400 rod cells, (C.) 0·014210 W. Strata in forms like the right-hand portion of 59, fig. 46, every now and then assuming the tongue-like formation 57, fig 46.

Fig. 43.



3.—Pressure 0·2 m.m., 263 M. The current of 1080 powder cells would not pass, but that of 1200 rod cells did so, producing strata, and the peculiar discharge entering the negative ring, as shown at *a*, fig. 43, (C.) 0·007631 W, with

200,000 ohms external resistance,			(C.) 0·003414 W,	there were	25 strata
300,000	„	„	(C.) 0·002675 W,	„	24 „
400,000	„	„	(C.) 0·002200 W,	„	23 „
500,000	„	„	(C.) 0·001866 W,	„	22 „
600,000	„	„	(C.) 0·001622 W,	„	21 „
700,000	„	„	the current would not pass,		
with 3,600 cells and,					
6,500,000 ohms		„	(C.) 0·000567 W,	there were still	21 strata.

4.—The exhaustion was carried still further, but as we did not at that time possess the McLeod gauge, which has been more recently attached to the

* C, when within brackets indicates that the value of the current, given in Webers, was obtained *approximately* by calculation; when not within brackets it indicates that the current was directly observed.

pumps, we cannot give the precise pressure; with 1200 rod cells, and an external resistance of 500,000 ohms (C.) 0·02414 **W**, there were 21 strata, as *b*, fig. 43, composed each of three differently coloured layers, the convex one, *a*, being blue bordered by a line of green, the middle, *b*, white, and the concave layer, *c*, reddish.* To the eye these strata were quite steady, but when examined with the rotating mirror, the blue convex layer was steady, while the reddish layer was shown to be flowing towards the negative. This phenomenon was better seen with 2400 rod cells, and an external resistance of 6,700,000 ohms, (C.) 0·000368 **W**.

5.—2400 cells and no external resistance, (C.) 0·014210 **W**. The illumination completely filled the tube, but with 500,000 ohms external resistance, (C.) 0·004718 **W**, there was a dark space of 7 inches between the last stratum and the negative pole.

6.—The exhaustion carried further. The current of 1200 cells passed intermittently, but with 2400 cells broad strata seven in 6 inches, were produced as in *c*, fig. 43, which, without resistance, at first extended to within 2 inches of, and then reached the negative pole.† With 5,670,000 ohms resistance the stratification became confused towards the positive pole.

7.—On carrying the exhaustion still further, the strata were fainter, bluer, and wider.

8.—After three more cistern-fulls of mercury had run through the SPRENGEL, the current of 2400 cells would not pass, and 3600 only gave a faint blue glow which pervaded the whole tube with indications of strata 2 inches broad, which the rotating mirror showed to be flowing towards the negative.

Air having through inadvertence been allowed to enter the tube, it was refilled with hydrogen and again exhausted.

Tube 129, *2nd Charge of Hydrogen.*

9.—Pressure 16 m.m., 21,053 **M**. 4800 cells at first passed, but it almost immediately afterwards required 8040 cells. The ring being positive, curiously formed luminous entities shot at intervals from it, remained stationary for a time, and then disappeared, to be replaced by others: the flow, as seen in the mirror, was towards the negative. The phenomena are depicted in 1, fig. 43.

The ring positive was illuminated with a red glow, the luminosities being bluish grey.

10.—Pressure 15 m.m., 19,737 **M**, 8040 cells. The luminosities produced are

* The tube having been subsequently re-attached to the pump when the McLEOD gauge was in connexion with it, the phase was reproduced at a pressure of 0·157 m.m., 207 **M**, 2400 cells, C. 0·01047 **W**.

† The phase was subsequently reproduced at a pressure of 0·046 m.m., 61 **M**, C. 0·00681 **W**.

shown in 2, fig. 43. The tube became very hot* in the immediate neighbourhood of the luminosities, which were very steady, but was much cooler at the negative and positive terminals, especially at the latter.

11.—Pressure 13 m.m., 17,105 **M**, 8040 cells. Luminosities were produced as the right hand diagram in 2, fig. 43; these were very blue, accompanied with great heat in their neighbourhood. In the rotating mirror the flow was seen to be towards the negative.

12.—The following day, the pressure being still 13 m.m., 8040 cells gave intermittent worm-like luminosities, 4, fig. 43, with the point negative: these did not occur when the point was positive.

13.—Pressure 12·2 m.m., 16,053 **M**, 8040 cells. The luminosities as in 5, fig. 43, when the point was negative. The flow of the luminosities was shown by the rotating mirror to be towards the negative. There was much heat developed in the neighbourhood of the luminosities, but little heat at the positive terminal, while the negative remained quite cool.

14.—Pressure 10·8 m.m., 14,211 **M**. Luminosities as in 6, fig. 43, which reminded one of a fish's mouth, especially as they opened and closed continually: they extended along 9 inches of the tube.

15.—Pressure 7·5 m.m., 9868 **M**, 8040 cells. 10 luminosities like the right-hand of diagram 2, fig. 43, but more pointed, the apex being agitated like the preceding fish-mouths.

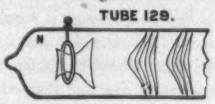
16.—Pressure 6 m.m., 7895 **M**, 5640 cells. The luminosities still more pointed; there was heat in the vicinity of the luminosities: 3240 just passed but the luminosities were confused.

17.—At a pressure of 1 m.m., 1316 **M**, the most beautiful phase of all was produced as shown in fig. 44, in some of its chief features; the current used was that of 2160 powder cells, (C.) 0·011520 **W**. The strata grouped themselves in threes and reached to within 6 inches of the negative ring; when 200,000 ohms resistance was introduced, (C.) 0·005658 **W**, the dark space extended to 9 inches. Only a portion of the luminosity about the negative ring is shown in the diagram; besides this, the ring was surrounded with a

* De La Rive (Archives Sci. Phys. Nat., xxvi., pp. 202–207) investigated the temperature of rarefied gases during the electric discharge. He employed a tube 160 m.m. long and 40 m.m. in diameter, with copper balls 10 m.m. in diameter for terminals. A pair of thermometers, whose mercury reservoirs were cylinders 30 m.m. long and 2·5 m.m. in diameter, were inserted each at a distance of 10 m.m. from its terminal. The conclusions drawn by him from his experiments are (i) that a sensible elevation of temperature accompanies the discharge in rarefied gases; (ii) that this elevation is sensibly less in the neighbourhood of the negative than near the positive electrode, provided that the gases are sufficiently rarefied, that the discharge passes easily, and that the light is stratified; (iii) that the absolute elevations near the two terminals and the differences of elevation vary with the density and nature of the gas. De La Rive remarks that these investigations are not to be confounded with those which have been made by Gassiot concerning the temperature of the terminals themselves.

cylindrical nebulosity of about a $\frac{1}{4}$ inch in diameter, and a glow filled up the end of the tube.

Fig. 44.



18.—Pressure 0·4 m.m., 526 **M**, 1200 cells. Strata produced resembling the four on the right of 58, fig. 46; the convex part being blue and the concave part pink; the last stratum, nearest to the negative, had two points; the negative ring was enveloped in a cylindrical nebulosity, pink close to the terminal, the strata reached within 5 inches of the negative terminal. There was seen in the rotating mirror a rapid flow *towards the positive*.

19.—Pressure 0·2 m.m., 263 **M**, 1200 cells, 100,000 ohms resistance. 16 perfectly steady grey strata like 14, fig. 43, a blue line on the convex face and pink on the concave, the negative discharge like that in the same figure. With 900,000 ohms resistance the number of the strata changed to 14.

20.—Pressure 0·2 m.m., 263 **M**, 1200 rod cells. 39 strata were produced as in 14, fig. 43, when 400,000 ohms resistance was in circuit, the convex side being blue and the broader concave side reddish, they extended to within 5 inches of the negative. With 50,000 ohms resistance, (C.) 0·005830 **W**, there were 34 strata. The luminosity at the negative is correctly shown in the diagram; no flow of strata could be detected by the rotating mirror, the image remaining steady.

21.—Pressure about 0·1 m.m., 132 **M**, 1200 cells, 500,000 ohms resistance. 21 strata as 14, fig. 43, very blue on the convex face, pink on the concave, the glow on the terminals pink. Observed with the rotating mirror the strata were steady, but from time to time secondary strata formed as 18, fig. 43, which were seen to flow towards negative.

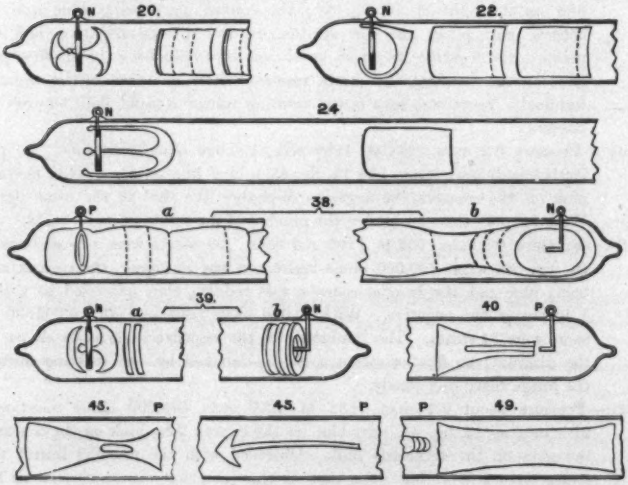
22.—The vacuum carried further by running $\frac{1}{3}$rd of a cistern-full of mercury through the pump; 1200 cells. 21 very blue strata, like *a*, fig. 43; with 100,000 ohms, still 21 strata; with 500,000 ohms, 22 strata; with 900,000 ohms the strata became like spheroids, being bounded on both sides by a convex face.

23.—The exhaustion was carried further, but the pressure was not measurable with our then means, the gauge appearing to stand higher than the barometer. The current of 1200 rod cells, (C.) 0·00763 **W**, did not pass very readily, and the strata were unsteady; the introduction of 50,000 ohms resistance, (C.) 0·005830 **W**, rendered them steady; they were 19 in number,

and from time to time narrower strata introduced themselves between those first formed, as shown in 18, fig. 43. The introduction of 900,000 ohms caused the strata to widen out and to fill the space occupied by the secondary strata.

24.—After 10 cistern-fulls had run through it required a potential of 2400 cells to pass, the strata were $1\frac{1}{2}$ inch wide, and a sort of hour-glass luminosity appeared at the negative, as shown in 20, fig. 45. At times the luminosity left the centre of the negative ring and jumped towards the wall of the tube, as shown in 22, fig. 45.

Fig. 45.



25.—At the 12th cistern-full the strata became $1\frac{1}{2}$ inch wide, but at times divided into two; one peculiarity observed was that the pink was on the convex side towards the negative and not as before noticed on the concave side.* The luminosity at the negative hugged the wall of the tube whether the point or the ring was positive. The phenomena are shown in 22, fig. 45. After a while 2400 rod cells only faintly illuminated the tube, and it required 3600 to continue the phase.

26.—At the 13th cistern-full 3600 cells would scarcely pass, only causing a faint glow in the tube, and it required 5880 to produce any strata; without

* The phase was subsequently reproduced at a pressure of 0·390 m.m., 513 M. C. 0·01451 W.

external resistance there were 10 very broad strata which extended from the positive to within 5 inches of the negative; the discharge at the negative was tri-furcated. The phenomena are shown in 24, fig. 45.

27.—At the 14th cistern-full the current of 6960 cells would not pass at first, but, after the charge of 8040 had been sent through, 5880 were sufficient. With 500,000 resistance 8 strata were produced as in 24, fig. 45. With 8040 cells the broad strata were crossed by bright lines not more than 0·1 inch apart. On the end of the central point of the negative discharge there was produced a pink half hour-glass addition, the point of which joined on to it at the centre of the ring. The two points of the negative discharge close to the tube were very sensitive to the approach of the finger.*

28.—At the 16th cistern-full it required 6960 cells to pass at first, but afterwards the tube became hot,† and the current of 2400 passed, the discharge taking place most readily when the point was negative. The phenomena were as in 20, fig. 45. The flow was from positive to negative.

29.—At the 17th cistern-full 5880 cells passed, but 6960 gave the best effect: 9 strata like 24, fig. 45, slightly pink, near the negative. The F line was seen with the spectroscope. A slow flow from the positive was seen with the rotating mirror. The next day the current of 2400 cells passed, producing a confused stratification; 3600 produced a more steady one. The negative discharge left the centre of the ring and hugged the side of the

* In his 'Notice sur l'appareil d'induction de Ruhmkorff, et les experiences qu'on peut faire avec cet instrument, 3me édition, Paris, 1857,' Du Moncel claims to have been the first to announce the attraction of the luminous discharge to the wall of the vacuum chamber when this is touched by the finger. Quet et Sequin ('Comptes Rendus,' xlvii., 1858, pp. 964–967) describe the effect of approaching the hand or a ring of tinfoil to a vacuum tube: the bright strata widen out on that side of the hand or tinfoil which is towards the positive terminal, and at the edge of the tinfoil, on the same side, a large dark space occurs—the phenomenon being best seen when the hand or tinfoil is near the positive terminal; on sliding the hand *towards* the positive the strata re-enter each other, but on sliding the hand *from* the positive they issue out again. Gassiot (Brit. Assoc., Aberdeen, vol. xxix. (sect.), p. 155), in speaking of strata being very sensitive to the finger in a cylinder 4½ inches in diameter and with the terminals 20 inches apart, says: "On the four fingers being placed in succession on the stratification they disappear in succession, and may be separated to a considerable distance by placing both hands on two separate portions of the cylinder."

† Frequently during the course of experiments with the tube 129 and others, when *highly* exhausted, it has required many cells to pass in the first instance, but when the tube had become heated a much smaller number sufficed.

Gassiot has also found that warming the tube promotes the passage of a current, and with regard to very low temperatures makes the following statement (Phil. Trans., 1859, p. 146):—"In a Torricellian vacuum which gave good cloud-like strata no change occurred when cooled to +32° Fah., but at −102° Fah. all traces of strata disappeared as well as the red glow around the negative; a glow throughout the tube remained. On heating the tube to the boiling point of mercury +600° Fah. the strata were likewise destroyed. When the mercury was frozen the stratifications disappeared, but a magnet made them reappear."

tube. On approaching the finger it was repelled to the opposite side of the tube, and sometimes split into two portions, one on each side of the finger.*

30.—At the 19½ cistern-full 3600 would not pass, 4800 sufficed when the point was negative; 7 broad strata crossed with lines of narrower strata not more than 0·02 inch wide and distant. A zone of intensely blue light, 0·25 inch broad, lined the inside of the tube around the point when negative. With 8040 cells the discharge was rustling when the point was positive, and if the primary of Apps's induction coil 819 was connected in circuit, a tell-tale tube being connected to the secondary, the tell-tale became illuminated, indicating an intermittent current.

31.—At the 22nd cistern-full, 4800 cells, no material change, except that between the blue zone and the end, the tube was filled with a pink glow, and that after a time even 8040 cells would not pass except when the point was negative; but the next day 2400 cells passed in either direction even with an external resistance of 4,900,000 ohms, gas having probably been given off from the glass walls.

32.—At the 29th cistern-full 8040 cells passed only when the point was negative, a milky light filling the whole tube; heat was generated at the negative, very great in proportion to the light.

33.—After 39 charges of the cistern had been sent through the Sprengel pump (since the vacuum had attained 0·2 m.m.) the current of 8040 cells would only pass after the contact with the battery had been maintained for some time and both ends of the tube alternately breathed upon; in fact, the current had to be coaxed through it.† There were 9 barrel-shaped strata produced as shown in 38, *a* and *b*, fig. 45; the illumination was very feeble, and no lines could be made out with the spectroscope either in the strata or the luminous glow around the negative terminal, in this case the straight wire. Examined with the hand spectroscope the spectrum appeared indeed to be nearly continuous. In the course of our experiments we have often observed great changes in the spectrum of hydrogen as the exhaustion became greater, the C line, for example, is the first to get faint and then to disappear.‡

34.—The tube had now a small charge of hydrogen let into it, which raised the pressure to 0·5 m.m., 658 **M**. 2400 rod cells with 500,000 ohms resistance in circuit, (C.) 0·004718 **W**, produced 54 beautiful steady strata, some of which threaded themselves on the straight wire when it was made negative, exactly as in the case of Geissler's tube 123 before alluded to; *b*, 59,

* The phenomenon was re-observed at a pressure of 0·038 m.m., 50 **M**, C. 0·00631 **W**.

† The limit of 8040 was subsequently attained at a pressure of 0·016 m.m., 21 **M**.

‡ The variation in the spectrum of the same gas under different circumstances has engaged the attention of several physicists—notably of Hittorf and Plücker (Phil. Trans. clv., 1865, pp. 1–30).

fig. 45, shows the appearance when the straight wire was negative, and *a* when it was positive. For a few seconds about 15 strata at the positive end became pink, all the others being grey; afterwards the strata in the middle of the tube were grey, those at each end being pink. The spectroscope did not show the F line distinctly. 4800 cells caused so much heat that the ring became red-hot and opened out and formed a sort of hook, as in 55, fig. 46.

Tube 129, *3rd Charge of Hydrogen.*

35.—Pressure 15·6 m.m., 20,526 **M**. At first the current of 4800 rod cells passed, giving a glow both at the positive and negative terminals; subsequently 5880 cells were necessary, and there shot across slowly from the positive the luminous entity 40, fig. 45. At first only 1 entity was formed, then 2, then 3, and lastly 4, the heat was great in their immediate vicinity; they flowed from positive to negative, and when the hand was approached as if to grasp them they receded from it towards the positive. After a short time a few strata were formed in the luminosities, as in 104, fig. 46. Ultimately 8040 cells were necessary, and the current only passed when the point was negative.

Tube 129, *4th Charge of Hydrogen.*

36.—Air being suspected, the tube was again filled with hydrogen and gradually exhausted; at 38 m.m., 50,000 **M** pressure, it was ascertained by means of the illumination of a tell-tale tube, No. 82, placed in the circuit, that a current of 8040 cells was passing when no illumination of the terminals of tube 129 could be seen, but possibly it may have passed on the outside of the tube. No. 82 has a resistance of only 16,000 ohms. Very soon afterwards, as the exhaustion was being continued by means of the water *trompe*, the terminals became illuminated.

37.—Pressure 13·5 m.m., 17,763 **M**, 8040 cells. One luminosity like 43, fig. 45, darted from either ring (distorted now like a hook) or straight wire, if positive, when it had reached the centre of the tube it darted back again. Ultimately 1, then 2, then 3 luminosities were produced. Great heat was evolved in the neighbourhood of these luminosities. In the spectrum the hydrogen lines C and F were very visible and air lines absent.

38.—Pressure 8·5 m.m., 11,184 **M**, 4800 cells. A glow about 4 inches long emanated from the positive, and then, intermittently, worm-like luminosities were formed as in experiment 12, but with this difference, that the worm-like entities were double one over the other nearly parallel to the axis of the tube.

39.—Pressure 7·8 m.m., 10,263 **M**. With 6960 cells, but better with 8040,

(C.) 0·042430 W, 16 luminosities resembling closely fig. 6, Plate 15, when 700,000 ohms resistance was introduced in the circuit, (C.) 0·008322 W, 3 arrow-headed luminosities were produced, each 4 inches long, the first adhering to the straight wire, positive, 45, fig. 45.

40.—Pressure 6·6 m.m., 8684 M, 8040 cells. 19 luminosities something like the fifth and sixth luminosities from the positive in fig. 7, Plate 15. The F and C lines were seen with the spectroscope, especially in the glow around the negative.

41.—Pressure 5·6 m.m., 7368 M, 4800 cells. 12 luminosities like fig. 6, Plate 15.

42.—Pressure 3·9 m.m., 5132 M, 4800 cells, 200,000 ohms resistance, (C.) 0·012420 W. 10 luminosities, part of one of which is depicted on the left of 49, fig. 45. From time to time there arose in the centre of the tube a concave spindle-like formation, 49, fig. 45, which gradually extended itself to both poles, and absorbed all the luminosities. Examined with the spectroscope the C and F lines were brilliantly seen in the glow around the negative terminal, but were not visible in the spectrum of the nebulosities, notwithstanding that they were brighter than the negative glow; there were blue, green, and red visible, but not the characteristic green and red lines of hydrogen.

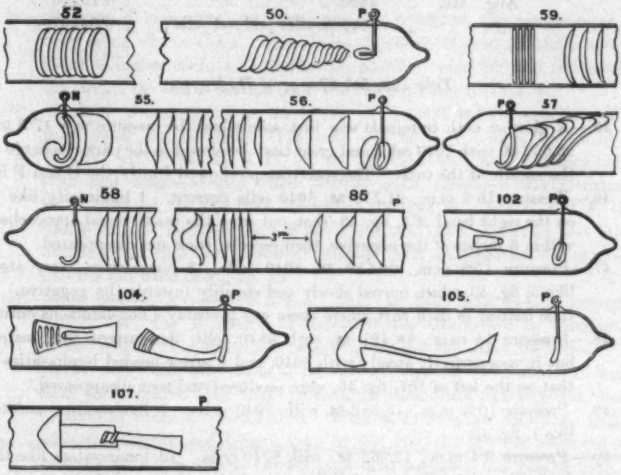
43.—Pressure 3·1 m.m., 4079 M, 4800 cells, (C.) 0·024970 W. A very curious phenomenon was presented, which has repeated itself on several occasions; at first the plane of the strata cut the tube at right angles, the strata being perfectly steady. An agitation was afterwards visible, and the strata arranged themselves diagonally as in 52, fig. 46, and almost immediately an agitated spiral* was formed, as 50, fig. 46, at the positive, extending nearly the whole length of the tube, but there were at the negative two or three saucer-shaped steady strata convex towards it. In the rotating mirror it was seen that there was a steady flow towards the negative. The characteristic hydrogen lines were very brilliant when the spectroscope was directed to the glow around the negative terminal, but quite a different spectrum was seen on a bright stratum, with mercurial lines in the orange. Shortly after this, the current being very great, the bent wire was heated to redness and fell down as in 56, fig. 46.

44.—Pressure 1·2 m.m., 1579 M, 3600 rod cells, (C.) 0·019940 W. A beautiful formation of 72 saucer-shaped strata from the positive, one of which is seen as about to detach itself, the other strata were less convex towards the middle of the tube, and lip-shaped near the negative, all being of a fine cobalt blue colour, 55, 56, fig. 46; on introducing 250,000

* Gassiot (Phil. Trans., 1858, p. 4) describes a somewhat similar appearance, thus (in a Torricellian vacuum): "As the mercury ascends in the tube the stratified discharge from the positive wire collapses, giving the appearance of a compressed spiral."

ohms resistance, (C.) 0·008504 W, they immediately became tongue-shaped and quite pink, 57, fig. 46; with 700,000 ohms, (C.) 0·004184 W, 113 perfectly steady pink strata were formed, and with 1,000,000 ohms, (C.) 0·003125 W, 90 strata, also pink, 58, fig. 46; with 6,900,000 ohms,

Fig. 46.



(C.) 0·000523 W, the tube was filled with paper-like strata 0·05 of an inch apart of a dull pink; with 12,000,000 ohms, (C.) 0·000304 W, they widened out to a distance of 0·2 inch, and were about 0·125 inch broad.

The tube was now removed from the pump and retained the characteristic property of showing blue strata with a large current, and changing to pink as resistances were introduced.*

Unfortunately, one of the glass cocks was accidentally broken off from 129, but the tube was repaired and again attached to the pumps on November 18, 1876. A series of experiments were made with it, the already described phenomena being reproduced, and many of them photographed.

Up to this time (August 4th, 1876) we had not made direct measurements of the currents passing in the tubes at the time of observing the

* According to Du Moncel, the change of colour on the introduction of resistance was first noticed by Ruhmkorff.

phenomena, but had merely taken observations of the deflections of the galvanometer with the batteries short-circuited, thus :—

May 25th, 1876,	3240	powder cells	. .	gave C.	0·03251 W.
Aug. 4th, „	„	„	. .	„	0·03858 „
May 25th, „	2400	rod	. .	„	0·12200 „
Aug. 4th, „	4800	„	. .	„	0·10410 „
„ „ „	8040	powder and rod cells	„	„	0·04901 „

Tube 129, *5th Charge of Hydrogen.*

45.—A glow at both terminals was first seen when the pressure was 17·2 m.m., 22,632 M, with 8040 cells, and great heat developed in the dark discharge near the middle of the tube. The spectroscope showed faintly the C and F lines.

46.—Pressure 16·5 m.m., 21,710 M, 8040 cells current. 1 luminosity like that on the right hand of 5, fig. 43, shot out from the positive and approached to within 6 inches of the negative, then receded back and disappeared.

47.—Pressure 15·8 m.m., 20,789 M, 8040 cells. 3 luminosities, very steady, like 5, fig. 43, which moved slowly and steadily towards the negative. The tube hottest in dark part where there was probably a non-luminous entity.

48.—Pressure 14 m.m., 18,421 M, with 6840 cells, the current was unsteady, but it was perfectly steady with 8040, and 6 arrow-headed luminosities like that on the left of 107, fig. 46, were produced and soon disappeared.

49.—Pressure 10·3 m.m., 13,552 M, with 8040 cells. 8 luminosities something like 1, fig. 43.

50.—Pressure 9·4 m.m., 12,368 M, with 8040 cells. 12 luminosities like those, fig. 7, Plate 15. The C and F lines seen in the glow around the negative.

51.—Pressure 7·7 m.m., 10,132 M, with 8040 cells. 10 luminosities like fig. 6, Plate 15, these ran together and disappeared and reappeared in a few seconds.

52.—Pressure 6·6 m.m., 8684 M, with 8040 cells. 12 luminosities very similar to those shown at fig. 5, Plate 15, the last adhering to the positive. The C line not visible in a nebulosity with the spectroscope, but that and the F line were both to be seen in the glow around the negative.

53.—Pressure 5·9 m.m., 7763 M, 8040 cells, C. 0·02056 W. 13 luminosities like those fig. 6, Plate 15. With 100,000 ohms, C. 0·01390 W, there were 10 luminosities not so wide as those when there was no resistance.

54.—Pressure 6·1 m.m., 8026 M, 8040 cells, C. 0·01910 W. At first 13 luminosities a little unsteady, then 11½ perfectly steady, like fig. 6, Plate 15. F and C visible in the glow around negative. F was not visible in a luminosity.

55.—Pressure 4·4 m.m., 5789 **M**, 8040 cells. 12 luminosities as depicted in fig. 6, Plate 15, which is copied from a photograph* obtained in 4 seconds.

56.—Pressure 4·0 m.m., 5263 **M**, 8040 cells. 15 luminosities as shown in fig. 7, Plate 15, taken from a photograph in 4 seconds.

57.—Pressure 3·6 m.m., 4737 **M**, 8040 cells, 30,000 ohms resistance. 15 luminosities almost touching, like fig. 7, Plate 15.

58.—Pressure 3 m.m., 3947 **M**, 4800 cells, C. 0·0362 **W**, the resistance of the tube being 88,600 ohms. There were 24 steady blue strata and a space of about 6 inches confused towards the positive; with 200,000 resistance in the circuit the strata became pink, the current being 0·01469 **W**.

59.—Pressure 1 m.m., 1316 **M**, 3600 cells, C. 0·03896 **W**, the resistance of the tube being 59,170 ohms. The tube was filled to within 1 inch of the negative with strata as in 85, fig. 46; all these were blue, but they turned pink and tongue-shaped when 200,000 ohms resistance was introduced, which reduced the observed current to 0·00782 **W**. The C and F lines visible in the luminosities. When 7,590,000 ohms resistance was introduced, a very close and somewhat agitated pink stratification was produced, like the left hand of 85, fig. 46.

60.—Some gas let in, pressure 3 m.m., 3947 **M**, 3600 cells gave a current of 0·04901 **W**; the resistance of the tube was ascertained by substituting 47,000 ohms wire resistance, which produced the same deflection. The strata were blue, like those of 55 and 56, fig. 46. For about 10 inches from the negative they took up an axial backwards and forwards steady rotation of about a quarter turn. With 174,000 ohms resistance, making with the battery and tube a total of 261,000, the current measured was 0·00879 **W**. The strata turned pink and assumed the tongue-form 57, fig. 46; with 783,000 ohms in circuit very close strata like the left hand of 85, fig. 46. In the rotating mirror a flow *towards the positive* was observed until a break occurred in the stratification; the flow was then irregular and backwards and forwards.

61.—Pressure 1·7 m.m., 2237 **M**. The current of 2400 cells passed: with 3600 cells the current was 0·03858 **W**, producing perfectly steady strata of which a photograph was obtained in four seconds; a facsimile of it is given, fig. 8, Plate 15. The strata were blue, but on introducing 500,000 resistance the current was reduced to 0·00175 **W**, and the strata turned pink and assumed the form fig. 9, Plate 15, which is a facsimile of a photograph obtained in 19 seconds.

62.—Pressure 0·8 m.m., 3600 cells (C.) 0·19940 **W**. A spiral series of tongues depicted in fig. 10, Plate 15, from a photograph which, however, could

* VARLEY, C. F. (Proc. Roy. Soc., xix., 1871, pp. 238-239) succeeded in photographing by an exposure of thirty minutes an *arch discharge* in a vacuum tube, so faint that in a perfectly dark room he was "sometimes unaware whether the current was passing or not."

scarcely be exposed long enough in consequence of the screw-like motion of the tongues. This motion appeared to be from positive to negative.* On introducing 900,000 ohms resistance, (C.) 0·003414 W, the tongues grouped themselves in pairs, of which there were 40, and changed from blue to pink. Examined with the spectroscope the line C had disappeared. The tube was connected with the condenser of 42·8 microfarads and 3240 cells, a resistance of 200,000 ohms being in circuit, (C.) 0·007461 W, the apparatus was arranged as in fig. 26, Part I. At the full potential, the same spiral series of blue tongues, quite steady, was produced, and these made a complete rotation in 30 seconds. On breaking connexion between the battery and condenser, the strata gradually changed to pink as the charge of the condenser ran down through the tube. A break-contact (direct) current was observed with the galvanometer in connexion with the secondary wire of coil 819, through the primary of which the current was made to pass; this tending to show that there was a pulsation of rapid decrease and gradual increase of flow through the tube.

Tube 129, *6th Charge of Hydrogen.*

63.—The tube, at 0·9 m.m., was partially charged with hydrogen by letting in 4 small calibrated charges, which increased the pressure each time 1·4 m.m., pressure 6·5 m.m., 8684 M, the resistance of the tube was found to be 170,000 ohms, and the total resistance of the whole 8040 cells, 130,000 ohms, or an average of 16·6 per cell. With 6960 cells the current, through the tube alone, was 0·02456 W, and there were produced 9 luminous entities as shown in fig. 5, Plate 15, taken from a photograph obtained in 1½ second.

64.—The gas in the tube at the same pressure, namely 6·5 m.m., 8040 cells, C. 0·02634 W. There were 7 entities as depicted in fig. 4, Plate 15, copied from a photograph obtained in one second.

65.—Pressure 6·5 m.m., on the introduction of 300,000 ohms resistance with 8040 cells, C. 0·0138 W, making a total resistance, inclusive of the tube and the battery, of 600,000 ohms, two luminosities were produced as seen in fig. 2, Plate 15, taken from a photograph obtained in two seconds, which, however, had to be corrected from a drawing, as there was a slight movement in the luminosities.

* De la Rive (Genève Mém. Soc. Phys. xvii., 1863, p. 72) describing the appearance of a nitrogen tube, says: "ces stries semblent former une hélice animée d'un mouvement de rotation autour de son axe."

Quet ('Comptes Rendus', xxxv., pp. 949–952) remarks that the apparent undulations and rotations of the strata vanish when single discharges are examined separately; the strata are then seen to have a fixed position throughout the entire column. [These phenomena are, however, distinct from that of experiment 62. D. and M.]

66.—Pressure 3·6 m.m., 4737 **M**, 4800 cells. Strata resembling 58, fig. 46, but near the negative the strata were indistinct. In the rotating mirror the distinct strata were steady, but in the indistinct portion there was indicated a rapid flow *towards the positive*. The lines C, F, and G seen in the glow around negative terminal, but C and G were not seen in the strata.

67.—Pressure 1·2 m.m., 1579 **M**, 2400 cells, C. 0·03251 **W**. 11 narrow strata, umbrella-shaped, about $\frac{3}{4}$ of inch wide, followed by two about $1\frac{1}{4}$ inch wide, then a confused discharge, in which the rotating mirror showed a rapid flow *towards the positive*. C, F, and G lines visible in the negative glow; G and C disappeared in the strata, and F was very faint.

68.—Pressure 1·9 m.m., 2500 **M**, 3600 cells, C. 0·04256 **W**. A very beautiful phase like 85, fig. 46.

Tube 129, *7th Charge of Hydrogen.*

69.—The tube was again recharged with hydrogen. Pressure 14·3 m.m., 18,816 **M**, 8040 cells. A glow was seen on both terminals.

70.—Pressure 13·8 m.m., 18,158 **M**, 8040 cells, C. 0·00703 **W**. 2 luminosities resembling the right hand of 2, fig. 43.

71.—Pressure 7·6 m.m., 10,000 **M**, 8040 cells. 8 luminosities, like fig. 5, Plate 15.

72.—Pressure 4·5 m.m., 5921 **M**, 8040 cells, C. 0·02881. 15 luminosities like fig. 7, Plate 15. In the glow around the negative terminal G, F, and C lines were seen, the last two brilliantly, but the luminosities gave a continuous spectrum.

73.—Pressure 3·1 m.m., 4079 **M**, 8040 cells, C. 0·03657 **W**. A tendency to the spiral formation 50, fig. 46.

74.—Pressure 1·2 m.m., 1579 **M**, 8040 cells, C. 0·04686 **W**. Strata like 58, fig. 46.

75.—Pressure far below 1 m.m., 8040 cells, C. 0·01412. 8 thickened strata like 22, fig. 45.

76.—The exhaustion carried still further. 8040 only passed with a faint glow, producing no deflection of a galvanometer which could indicate a current of 0·00024 **W**. The secondary current of Apps's induction coil 821 passed, producing 6 thick strata like 22, fig. 45.

Tube 129, *8th Charge of Hydrogen.*

77.—Pressure 11·5 m.m., 15,132 **M**, 8040 cells, C. 0·00993. At first the tube was only faintly illuminated at the two terminals, with a barely visible glow throughout the tube, which became heated in the middle, then one luminosity formed at the positive 102, fig. 46. This moved several inches from

it, and then returned to it again to move slowly away, the current was still 0·00993 W. The calculated resistance of the tube at this pressure is 688,900 ohms.

78.—Pressure 10·1 m.m., 13,289 M, 8040 cells, C. 0·00993 W. At first only a glow at both terminals, the tube became hot in the middle, a barely visible glow throughout the tube; then one luminosity as shown on the left of 104, fig. 46, which travelled slowly to within 3 inches of the negative, and was followed by a second luminosity, as seen in the same figure. The C and F lines could be seen with the spectroscope in the glow around the negative terminal, the spectrum of a nebulosity was nearly continuous.

79.—Pressure 10·2 m.m., 13,421 M, 8040 cells, C. 0·01158 W. One arrow-headed nebulosity, 105, fig. 46; the resistance of the tube was 570,000 ohms.

80.—The tube in the same state; the induced current of Apps's coil, No. 821, producing a 6-inch spark, passed like the streamer discharge of the battery in air, as shown in Part I., page 88, fig. 16. The discharge in the tube is shown in fig. 47, which brings out strongly the effect of great difference of potential on the phenomena, and also supports the hypothesis that the discharge in partially exhausted tubes is of the same nature as through air at ordinary atmospheric pressure—a disruptive one.*

Fig. 47.

81.—Pressure 8·1 m.m., 10,658 M, 8040 cells, C. 0·01331 W. 7 luminosities, part of them arrow-headed, arranged in a wavelike formation, the nebulosity nearest the positive entering one of the arrow-headed ones next to it, as shown 107, fig. 46. The resistance of the tube was 477,000 ohms.

82.—Pressure 6·8 m.m., 8947 M, 8040 cells, C. 0·0184 W. 10 nebulosities similar in character to 107, fig. 46. Resistance of the tube 304,900 ohms.

83.—Pressure 4·3 m.m., 5658 M, 5880 cells, C. 0·02371 W, resistance of the tube 175,100 ohms. 13 luminosities were obtained like fig. 7, Plate 15. The G, F, and C lines were visible in the glow around the negative terminal, but they were not visible in the nebulosities.

84.—Pressure 1 m.m., 1316 M. 2400 cells passed, with 3600 the current was 0·03251 W, the same phase as 85, fig. 46.

* Gassiot (Phil. Trans., 1858, p. 5) describes a similar discharge as a wavy line. His tube, when cooled by a freezing mixture of ice and hydrochloric acid, gave striæ.

Tube 129, *9th Charge of Hydrogen.*

85.—Pressure 14·1 m.m., 18,533 **M**, 8040 cells, C. 0·00335 **W**. A glow from the positive extending for $\frac{2}{3}$ the length of the tube; it began to taper down about half the length of the tube, and then great heat was developed at its extremity.

86.—Pressure 12 m.m., 15,789 **M**. A luminosity formed on the positive, like 102, fig. 46; it then travelled nearly to the negative and returned slowly to the positive. After a while another luminosity partly stratified, formed behind the first at the positive, but ultimately disappeared. Finally the luminosity took the form of 104, fig 46, and was partially stratified, it moved towards the negative when the markings became more pronounced, but when returning to the positive the markings disappeared.

87.—Pressure 2 m.m., 2632 **M**, 3600 cells, C. 0·01272 **W**. The phase was obtained which is shown in fig. 11, Plate 15, copied from a photograph taken in 7 seconds.

The tube was accidentally broken on January 23rd, 1877, and although it has been successfully mended it has not been re-filled, as the pumps have been occupied with other experiments.*

Tube 129, *Air.*

88.—Pressure 8·7 m.m., 11,447 **M**, 8040 cells. A continuous nebulous discharge, most brilliant at the positive wire, a patch of nebulous light on the negative ring.

89.—Pressure 5·5 m.m., 7237 **M**, 8040 cells. Three nebulous luminosities like 1, fig. 48.

90.—Pressure 2·4 m.m., 3158 **M**, 4800 cells. A continuous glow extending from the positive to the negative, in which the rotating mirror did not show any structure, C. 0·02320 **W**.

91.—Pressure 1·2 m.m., 1579 **M**, 3600 cells. Two or three strata formed at the extremity of the nebulous discharge near the negative.

* May 20th, 1878. This tube has since been re-attached to the pump, and several of the foregoing experiments have been repeated. The effect of running successive cisternfulls of mercury through the pump after the pressure had attained 0·18 m.m. was found to be as follows:—

1st	cisternfull	reduced	the	pressure	to	0·085	m.m.,	112 **M**,	3,600	cells, C. 0·01451 **W**,	21 strata.
2nd	,,	,,	,,	0·038	,,	50	,,	,,	,,	,, 0·00631 ,,	15 ,,
3rd	,,	,,	,,	0·019	,,	25	,,	7,760	,,	,, 0·02131 ,,	20 ,,
5th	,,	,,	,,	0·011	,,	14	,,	,,	,,	,, 0·01705 ,,	17 ,,
8th	,,	,,	,,	0·008	,,	11	,,	8,040	,,	,, 0·01331 ,,	indistinct.
9th	,,	,,	,,	0·003	,,	4	,,	11,000	,,	,, 0·01639 ,,	faint.
10th	,,	,,	,,	0·002	,,	3	,,	,,	,,	,, 0·01840 ,,	,,

92.—Pressure 0·5 m.m., 658 **M**, the current of 2400 rod-cells passed. With 3600, C. 0·03071 **W**, there was a nebulous discharge from the positive almost reaching the negative, near which a few strata were formed. On disconnecting the battery the *gas* in the tube was observed to be phosphorescent and the phosphorescence continued for 6½ seconds.* The nebulous discharge was salmon coloured, not at all like the red discharge of a nitrogen vacuum.

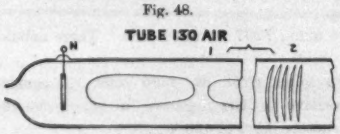
93.—Pressure had increased without leakage to 0·6 m.m., 789 **M**, 2400 cells, with 200,000 ohms resistance, C. 0·00527 **W**. There were produced, commencing at the positive wire, 21 well defined and perfectly steady strata, about 1 inch thick, like *c*, fig. 43, very bright at the convex face: the glow round the negative was cylindrical. The resistance of the tube was reproduced by the insertion of 90,000 ohms in place of the tube.

Tube 130, *Air*.

94.—Tube 130, charged with air and exhausted to a pressure of 8 m.m., 10,526 **M**, 8040 cells. One luminosity from the ring when positive, about 12 inches long.

95.—Pressure 4 m.m., 5263 **M**, 8040 cells. A continuous nebulous discharge, carmine in colour, from the point positive, reaching nearly to the negative where there was formed a separate luminosity, as represented in 1, fig. 48; with 200,000 ohms in circuit, the nebulous discharge from the positive separated into two luminosities making, with that at the negative, three in all.

Fig. 48.



96.—Pressure 3·5 m.m., 3605 **M**, 8040 cells. Strata were produced as in 2, fig. 48, but the discharge was confused in the greater part of the tube.

* Gassiot (Dec. 1858—Phil. Trans. 1859, p. 137) says, "in some tubes (Geissler's) for several seconds after the discharge had ceased the tubes remained throughout their entire length phosphorescent." About the same time Becquerel, whose attention had been directed to this phenomenon by Ruhmkorff, communicated the result of his observations to the *Académie des Sciences* ('Comptes Rendus,' xlvii., 1859, pp. 404–406). The subject has since been investigated and discussed by Morren ('Comptes Rendus,' liii., 1861, pp. 794–795); Sarasin (Archives Sci. Phys. Nat. xxxiv., 1869, pp. 243–254; Ann. de Chim. xvii., 1869, pp. 501–502; Poggend. Annal. cxl., 1870, pp. 425–434); De la Rive ('Comptes Rendus,' lxviii., 1869, 1237–1238; Ann. de Chim. xix., 1870, pp. 191–192); Hittorf (Ann. de Chim. xvii., 1869, pp., 487–496), and others.

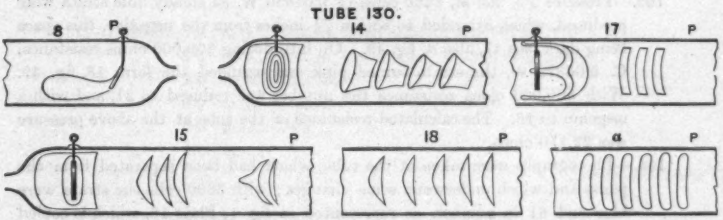
Tube 130, *Hydrogen.*

97.—The tube was exhausted and filled ten times successively with dry hydrogen. Pressure 18 m.m., 23684 **M**, 8040 cells. There were specks of light visible at both terminals but the discharge in the tube was non-luminous, great heat being developed about the middle of the tube.

98.—Pressure 13·7 m.m., 18,026 **M**, 8040 cells. There was one luminosity at the ring positive. Connected with the secondary of an induction coil instead of a battery, there was a streamer discharge like that produced under similar circumstances in tube 129, 106, fig. 47.

99.—Pressure 11·8 m.m., 15,526 **M**. Still one luminosity, 8, fig. 49; in the rotating mirror the reflection appeared like a fine diaper pattern, indicating a rapid motion in alternate directions.

Fig. 49.



100.—Pressure carried down by successive steps to 5·6 m.m., 7368 **M**, 8040 cells. The tube was filled with a nebulous discharge crossed by paper-like stratifications, the current was intermittent. The C, F, and G lines visible with the spectroscope in the nebulous illumination of the negative terminal, but the C and G lines were not visible in the strata; with 700,000 to 900,000 ohms resistance the nebulous discharge broke up into three distinct luminosities.

101.—Pressure 2·4 m.m., 3158 **M**, 3600 rod cells, strata like 17, fig. 49, in shape, but closer and agitated; a flow seen in the mirror *towards the positive.*

102.—Without any external leakage, the pressure had increased the following day to 3 m.m., 3947 **M**, 3600 rod cells; luminosities as depicted in 14, fig. 49, extended half the length of the tube towards the positive, the second half on the positive side being filled with nebulous ill-defined strata; the discharge on the ring, negative, being cylindrical.

103.—Pressure 1·2 m.m., 1579 **M**, 3600 rod cells. This was the first occasion of

regular steady strata being observed with this tube, as shown in 15, fig. 49, resembling those seen in tube 129, 55 and 56, fig. 46, at the same pressure. It is curious that up to this pressure tube 130 had throughout only given agitated discharges, and had shown no signs of distinct well-formed luminosities. The only difference between tubes 129 and 130 is that the latter has a diameter of 1·75 inch, or 0·125 inch less than that of the former; it is 32 inches long, 28 inches between the terminals. The strata were blue, with the exception of the first and second from the negative, which, as well as the cylindrical glow on and about the negative, were pink. With 1,000,000 ohms resistance the strata turned pink. It was noticed that on first closing the circuit the strata were agitated, but after a while they became steady, the tube in the meantime becoming heated.

104.—Pressure 1·0 m.m., 1316 **M**, 3600 rod cells, 200,000 ohms resistance in circuit, steady blue strata like the three middle ones in 15, fig. 49. With 1 megohm resistance the strata became pink.

105.—Pressure 0·2, 263 **M**, 2400 cells, C. 0·04686 **W**, 34 steady blue strata were produced, which extended to within 7½ inches from the negative, this space being dark, see 17, also *a*, fig. 49. On introducing 200,000 ohms resistance, C. 0·00879 **W**, the strata turned pink and assumed the form 18, fig. 49. With 500,000 ohms resistance the number was reduced to 21, and with a megohm to 16. The calculated resistance of the tube at the above pressure was 22,170 ohms.

106.—Photographs were taken of the tube, which had been separated from the pump and which underwent some changes; with 3600 cells the strata were blue and 61 in number, as represented in fig. 1, Plate 16, which is copied from a photograph obtained in 11 seconds.

107.—With 700,000 ohms resistance in circuit the strata were reduced to 18, and turned pink. Fig. 2, Plate 16, from a photograph taken in 90 seconds.

108.—Subsequently another change occurred in the phenomena of the tube with 3600 rod cells, the phase being most splendid, and showing 21 double strata intensely blue, but with a *carmine line* between the components.* The tube

* Gassiot (Brit. Assoc., 1865 (sect.), p. 15): "On the change of form and colour which the stratified discharge assumes when a varied resistance is introduced in the circuit of an extended series of the voltaic battery." [4000 cells carbon and amalgamated zinc, in each cell a table-spoonfull (24 c.c.) of sulphate of mercury]. The resistance in the circuit was a tube ¼ an inch in diameter and 3 feet long, filled with water, in which two platinum wires could be inserted to different depths:—

"On depressing the wire small crescent-shaped disks of red light are observed to be rapidly produced in quick succession from the positive pole. Shortening the resistance one by one disappear at the positive until 19 remain; on still lessening resistance two disks near the negative join together, assuming the form of a double convex lens, the side near the *negative being of a slight blue tinge, that towards the positive*

was detached November 17, 1876, and now, March 16, 1878, it still shows this beautiful phase. Fig. 3, Plate 16, represents the phenomena; it is copied from a photograph obtained in 40 seconds.

109.—On introducing 900,000 ohms resistance, the same number of cells being used, 26 pink strata were produced, as shown in fig. 4, Plate 16, from a photograph obtained in 90 seconds.

Tube 139, *Air.*

110.—Pressure 13·5 m.m., 17,763 **M**, 8040 cells. A long nebulous discharge reaching within 6 inches of the ring negative, which was illuminated with a cylindrical glow, the intervening space being non-luminous.

Tube 139, 1*st Charge of Hydrogen.*

111.—Pressure 5·9 m.m., 7763 **M**, 8040 cells, C. 0·02007 **W**.

,,	3·0	m.m., 3947 **M**,	the current of	4800	cells passed.
,,	2·0	m.m., 2632 **M**,		3600	,,
,,	0·9	m.m., 1184 ,,		2400	,,
,,	0·6	m.m., 789 ,,		,,	,,
,,	0·03	m.m., 39 ,,*		,,	,,
,,	,,	,, ,, ,,		,,	,, with 4,000,000 ohms.
,,	0·01	m.m., 13 ,,		3600	,,

112.—Pressure 0·03 m.m., 39 **M**, 2400 cells, 4,000,000 ohms resistance, a phase was produced resembling 11, Plate 16.

Tube 139, 2*nd Charge of Hydrogen.*

113.—Pressure 16·7 m.m., 21,974 **M**, 8040 cells, just passed.

114.—Pressure 14·9 m.m., 19,605 **M**, 8040 cells, C. 0·00386 **W**. A glow extending from the positive half the length of the tube.

115.—Pressure 12 m.m., 15,789 **M**, 8040 cells. One luminosity as 3, fig. 50,

a reddish fawn, and the centre a brilliant red colour. As resistance is decreased two successively join. When resistance is removed all the 19 strise assume the double convex form, the red central line continuing. . . . . On the sides of the tube where four or five of the disks near the negative impinge there remained a black deposit."

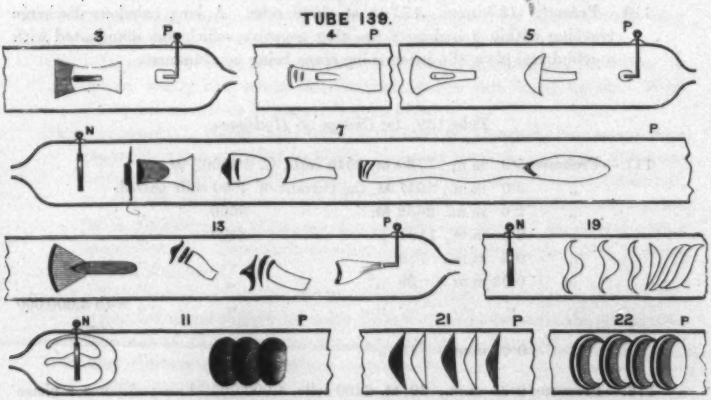
* Jan. 11, 1877. We had at that date the McLeod gauge connected with the pumps.

reminding one of 102, fig. 46, which shows a phase of tube No. 129 at 11·5 m.m., 15,132 **M**.

116.—Pressure 10 m.m., 13,158 **M**, 8040 cells. The luminosity assumed the form 4, fig. 50, closely resembling tube 129 at 10·1 m.m., 13,289 **M**, the left of 104, fig. 46.

117.—Pressure 9·04 m.m., 11,895 **M**, 8040 cells, C. 0·01412 **W**. Two luminosities as 5, fig. 50, recalling tube 129, at a pressure of 9·1 m.m., 11,974 **M**, 107, fig. 46, but in the latter the arrow-headed precedes the other luminosity.

Fig. 50.



118.—Pressure 6·319 m.m., 8314 **M**, 8040 cells. Three arrow-headed luminosities as depicted in fig. 3, Plate 15, copied from a photograph and a drawing made at the time. The photograph was obtained in 2 seconds.

119.—Pressure 4·1 m.m., 5395 **M**, 6960 cells, C. 0·0232 **W**. The luminosities as depicted in 7, fig. 50; the first near the negative having a peculiar flat-hat-like form, behind which are some strata convex towards the positive.

120.—The exhaustion was continued, but no regular strata could be obtained until the pressure had fallen to 0·823 m.m., 1082 **M**, when with 2400 cells strata, twelve in number, like the first on the left in 21, fig. 50, were produced, the rest of the discharge towards the positive being confused.

121.—Pressure 0·518 m.m., 682 **M**, 2400 cells. Nineteen saucer-shaped strata were formed, and from time to time fainter strata flashed in between them, the phenomena resembling fig. 5, Plate 16.

122.—Pressure 0·12 m.m., 158 **M**, 2400 cells, C. 0·01772 **W**. Only a nebulous discharge, but on introducing 500,000 ohms thick strata were produced, as 11, fig. 50; the discharge at the negative ring was trifurcated, the central arm passing through the centre of the ring.

123.—Pressure 0·03 m.m., 39 **M**. The current of 3600 cells passed.

Tube 139, *3rd Charge of Hydrogen.*

124.—Pressure 9·331 m.m., 12,276 **M**, 6960 cells, C. 0·00703 **W**. One luminosity like tube 129, 40, fig. 45.

125.—Pressure 8·548 m.m., 11,249 **M**, 6960 cells, C. 0·01234 **W**. Four luminosities arranged in serpent-like form, as shown in 13, fig. 50.

126.—The pressure had risen without any leakage to 9·502 m.m., 12,526 **M**, 6960 cells. One luminosity like that on the left hand in 13, fig. 50. A photograph was obtained in 10 seconds but has not been copied. Another photograph obtained in 1 minute is shown in fig. 1, Plate 15; it will be observed that it has a spear-head continuation towards the negative.

127.—Pressure 6·562 m.m., 9344 **M**, 6960 cells. 10 luminosities like those in fig. 5, Plate 15. These ran together to form only two, and separated again into ten, the mouth-like ends towards the negative being in continual vibration.

128.—Pressure 4·615 m.m., 6073 **M**, 5880 cells, C. 0·02693 **W**. A series of luminosities, the first near the negative ring being the flat-hat-shape like 7, fig. 50, the remainder like fig. 7, Plate 15.

129.—Pressure 3·291 m.m., 4330 **M**, 5880 cells, C. 0·00939 **W**. Strata curiously curved, some with a concavity towards the negative, the remainder having a tendency to arrange themselves in a spiral, 19, fig. 50. The current of 4800 cells passed, but that of 3600 would only do so when the point was negative.

130.—Pressure 1·304 m.m., 1717 **M**, 2400 rod cells, C. 0·02136 **W**. Umbrella-shaped strata well defined towards the negative, but confused towards the positive.

131.—Pressure 1·244 m.m., 1637 **M**, 2400 cells, C. 0·01561 **W**.

132.—Pressure 0·401 m.m., 528 **M**, 2400 cells. Umbrella-shaped, slightly unsteady strata were obtained, between which other fainter ones introduced themselves from time to time: this phase is shown at 21, fig. 50, and also in the copy of a photograph, obtained in 10 seconds, fig. 5, Plate 16: these strata were blue. The same phase was obtained in experiment 121 at a pressure of 0·518 m.m. By the introduction of 700,000 resistance, C. 0·00088 **W**, 23 strata were obtained of a pink colour perfectly steady, as represented in fig. 6, Plate 16, copied from a photograph obtained in 20

seconds. The strata altered in form, afterwards becoming like 22, fig. 50, the convex face being green, the middle blue, and the concave face reddish. The C and F lines were seen with the spectroscope directed on the glow around the negative.

133.—Pressure 0·3425 m.m., 451 **M**, 2400 rod cells, C. 0·01272 **W**. Strata like those in tube 129, *a*, fig. 43, obtained with a pressure estimated at 0·2 m.m., 263 **M**, but which we had not then the means of measuring. With 200,000 ohms resistance current was reduced to 0·00580 **W**.

134.—Pressure 0·2608 m.m., 343 **M**, 2400 cells, C. 0·01102 **W**. A phase produced as shown in fig. 8, Plate 16, copied from a photograph obtained in 40 seconds.

135.—Pressure 0·1204 m.m., 158 **M**, 3600 cells, C. 0·01771 **W**. A phase as shown in fig. 10, Plate 16, copied from a photograph obtained in 27 seconds.

136.—Pressure 0·1103 m.m., 145 **M**, 3600 cells, C. 0·01575 **W**. A phase of 23 strata as shown in fig. 9, Plate 16, copied from a photograph obtained in 15 seconds.

137.—Pressure 0·051 m.m., 67 **M**, the current of 3600 cells passed intermittently; 4800 cells, C. 0·00191 **W**, produced a continuous illumination from the positive to within 3 inches of the negative, the discharge at the negative licking the inside of the tube as in fig. 11, Plate 16.

138.—Pressure 0·01 m.m., 13 **M**, the current of 4800 rod cells just passed: with 6960 cells the current produced no appreciable deflection of our galvanometer which would indicate 0·00024 **W**. The strata, it will be perceived, have thickened and become much wider as shown in fig. 11, Plate 16, copied from a photograph obtained in 7 seconds. The discharge at the negative licked the side of the tube and was very sensitive to the approach of the finger.

139.—By standing 16 hours the pressure had somewhat increased without leakage having occurred, and was 0·037 m.m., 49 **M**, 6960 cells, current less than 0·00024 **W**; the discharge was milky white and quite different from anything before seen with a hydrogen residual charge. The strata had become still broader, as seen in fig. 12, Plate 16, copied from a photograph, the negative discharge hugging the tube and being very sensitive to the finger. The C and F lines could not be seen with the spectroscope, but there was a double green line near *b*.

140.—A charge of hydrogen was let in, being the contents of the india-rubber tube between the glass cock on tube 139, and the cock on the four-way junction-piece, F, fig. 35; the charge was 0·001725 of the capacity of the tube and pump, and increased the pressure to 1·311 m.m., 1725 **M**. 3600 rod cells produced a stratification composed of umbrella-shaped strata, united in the middle of the tube by a luminosity one-third the length of the tube. The double green line near *b* had disappeared and the C, F, and G lines were visible in the spectroscope.

141.—Another calibrated charge of hydrogen was let in and raised the pressure to 2·622 m.m., 3550 **M**; the current of 3600 cells just passed: with 4800 cells a phase was produced resembling tube 129, fig. 7, Plate 15.

142.—Another calibrated charge of hydrogen increased the pressure to 3·933 m.m., 5175 **M**; 4800 rod cells just passed, but it required 5880 cells to produce a steady phase; there were luminosities produced arranged in an irregular spiral, resembling 13, fig. 50.

143.—The pump was worked and the pressure reduced to 2·548 m.m., 3343 **M**, 3600 rod cells, C. 0·02209 **W**. Strata were produced as in 19, fig. 50, with a distinct spiral formation after the first five strata near the negative. These five strata at last assumed a direction in a curved line, and took up a rapid spiral rotation at first from the bottom towards the top of the tube, and afterwards in the opposite direction.

144.—Pressure 0·7836 m.m., 1031 **M**; 1200 cells would not pass; 2400 did; but the best effects were obtained with 4800 rod cells, which gave a current of 0·03251 **W**, producing 17 beautiful and very blue strata, shown in fig. 6, Plate 16, copied from a photograph. In the spectroscope the double line near *b* was seen as well as C and F.

145.—Pressure 0·7626 m.m., 964 **M**, 3600 cells, C. 0·02544 **W**. A phase of tongue-shaped strata, as shown in fig. 7, Plate 16, which is copied from a photograph obtained in 8 seconds.

146.—Two calibrated charges let into the tube raised the pressure to 1·033 m.m., 1359 **M**; 3600 cells, C. 0·02825 **W**. 22 strata, in shape like those of 21, fig. 50.

147.—More charges of hydrogen were let in and the pump worked to bring the tube to a good phase, it was then detached from the pump, January 29, 1877, and on March 11, 1878, it had not altered, giving with 3600 cells, C. 0·03368 **W**, 24 beautifully blue strata, and with 300,000 ohms resistance inserted, C. 0·00782 **W**, 18 pink strata.

Tube 140, 29 *inches between the terminals, Hydrogen.*

148.—Pressure 2·402 m.m., 3160 **M**, 5880 cells. A phase like fig. 51, but the strata more agitated towards the positive.

Fig. 51.

TUBE 140.

149.—Pressure 1·721 m.m., 2264 **M**, 3600 cells, C. 0·10050 **W**. A phase as in fig. 51. The G, F, and C lines seen in the spectroscope.

In consequence of a crystalline deposit having formed in the tube it was detached from the pump in order to ascertain its nature: it was insoluble in bisulphide of carbon, water, alcohol, nitric, hydrochloric, or strong sulphuric acids, but by heating the tube with a spirit lamp, a little strong sulphuric acid having been previously inserted, the substance came off in yellow flakes and proved to be sulphur which was now soluble in bi-sulphide of carbon. It had existed in the first instance in one of its allotropic conditions. It was ascertained that the source of the sulphur was the vulcanized india-rubber junction tube from which it was gradually taken up by the current of hydrogen. This tube was replaced by another, 0·4 inch in diameter with 0·1 inch bore, made of ordinary india-rubber, but it was found necessary, notwithstanding its thickness, to support it by the insertion of a helix of platinum wire 0·0125 inch in diameter.

Tube 132, *Air.*

26 inches between the terminals, 1·75 inch diameter.

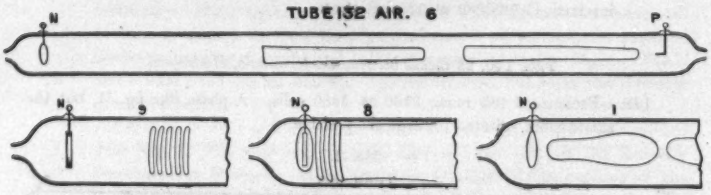
150.—Pressure 13 m.m., 17,105 **M**, 8040 cells would not pass; pressure 11·6 m.m., 15,263 **M**, the current just passed.

151.—Pressure 9·3 m.m., 12,237 **M**, 8040 cells. A faint glow about 6 inches long when the ring was positive.

152.—Pressure 6·3 m.m., 8289 **M**. 8040 cells passed at first and several luminosities emanated from the positive, but after a while they disappeared and could not be reproduced. The illumination was feeble but the amount of heat generated was great in proportion to the light.

153.—Pressure 6 m.m., 7895 **M**, 8040 cells. Six luminosities were produced when the ring was positive, as shown in 1, fig. 52.

Fig. 52.



154.—Pressure 4·9 m.m., 6447 **M**, 6840 cells. Four similar luminosities, 1, fig. 52, which were reduced to two on introducing 500,000 ohms into the circuit. These luminosities issued at the rate of about one per second from the positive, and when there were three, the middle one approached that emanating

from the positive and absorbed it, leaving two. The current of 5640 cells would not pass. Similar phenomena were observed when the pressure had been lowered to 3·8 m.m., 5000 **M**.

135.—Nothing worth noting occurred until the pressure had been lowered to 2·1 m.m., 2763 **M**; the current of 3600 cells passed, producing an agitated discharge: the introduction of 50,000 ohms made the discharge steady, and two luminosities, 6, fig. 52, were produced; these pulsated and coalesced to form one, then separated into two; this phenomenon was repeated rythmically at regular intervals.

156.—Pressure 1·1 m.m., 1447 **M**. 2400 rod cells would not pass, but with 3600 there was a continuous luminosity nearly filling the bore of the tube to within a short distance of the negative ring, where there were three strata, 8, fig. 52.

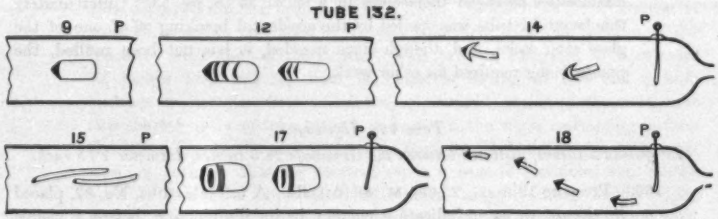
157.—A slight increase of pressure without leakage; pressure 1·2 m.m., 1579 **M**, 3240 powder cells. A rapidly flowing stratification from the negative *towards the positive*, 9, fig. 52.

Tube 132, *1st Charge of Hydrogen.*

158.—The tube was filled with hydrogen and exhausted at first with the water *trompe*, which reduced the pressure to within 12 m.m., 15,789 **M** of the barometer. The tube was washed out several times with hydrogen and exhausted between each filling.

159.—Pressure 16·2 m.m., 21,316 **M**. The current of 8040 cells passed illuminating the terminals.

Fig. 53.



160.—Pressure 6·9 m.m., 9079 **M**. 5640 cells produced five luminosities, as 9, fig. 53, which after a time fell off to three, and were slightly trembling. Compare this phase with 1, fig. 52, when at nearly the same pressure the tube was charged with air. The discharges were all agitated, even when the pressure had been reduced to 1 m.m. The cause of this was found to be a broken cell in one of the batteries.

Tube 132, *2nd Charge of Hydrogen.*

161.—After repeated exhaustions, fillings, and re-exhaustions the pressure was reduced to 19 m.m., 25,000 **M**. With 8040 cells there was an intermittent flash of light through the tube, whether the point or ring were positive.

162.—Pressure 11·8 m.m., 15,526 **M**. Three worm-like luminosities with 8040 cells.

163.—Pressure 7·8 m.m., 10,263 **M**, 8040 cells. Eight luminosities as depicted in 12, fig. 53.

164.—Pressure 6·2 m.m., 8158 **M**, 8040 cells. 12 very similar luminosities, but on introducing 500,000 ohms into the circuit they changed to arrow-headed entities, as 14, fig. 53; the introduction of 1,000,000 ohms changed them into parallel worm-like entities, 15, fig. 53. With 4,500,000 ohms resistance all the luminosities disappeared, a nebulous light reaching from the positive half-way towards the negative, the interval between it and the negative being quite free from light. This nebulous light shrank in a few seconds up to the positive and disappeared, leaving a faint glow on the positive terminal. The above description will render evident how great a variety of phenomena may be produced by varying the current through a tube at a constant pressure.

165.—Pressure 4·5 m.m., 5921 **M**. The current of 5640 passed: both with this number, and with 8040 cells the same phenomena were produced without external resistance, namely thirteen beautiful blue luminosities as 17, fig. 53, agitated near the positive, but perfectly steady in other parts of the tube. With 8040 cells and 800,000 ohms resistance, a series of small arrow-headed luminosities arranged themselves in a spiral, as 18, fig. 53. Unfortunately this beautiful tube was spoiled by the accidental breaking off of one of the glass stop cocks, and, though since mended, it has not been refilled, the pumps being required for other work.

Tube 148, *Hydrogen.*

Length 32·5 *inches, distance between the terminals* 28·5 *inches, diameter* 1·75 *inch.*

166.—Pressure 18 m.m., 23,684 **M**, 8040 cells. A tell-tale tube, No. 82, placed in circuit, so as to indicate a current by its illumination, before a visible glow occurred in the large tube. 8040 cells, a current too small to measure, and evident only in the tell-tale tube.

167.—Pressure 10·5 m.m., 13,816 **M**, 8040 cells; C. 0·00580 **W**. Three luminosities with arrow heads arranged in a spiral, like 14, fig. 53, which in a few minutes settled down to one entity, with the characteristic form shown in 3, fig. 50, in the case of tube 139, at a pressure of 12 m.m. There was

much heat developed in its immediate vicinity, the remainder of the tube being cool.

168.—Gas was let in, and the pressure raised to 15 m.m., 19,737 **M**, 11,000 cells. No luminosity at the positive, but a faint one at the negative, not unlike 3, fig. 50, in general shape, but twice as long, without any markings of brighter light.

169.—Pressure 13 m.m., 17,105 **M**, 11,000 cells. A serpentine line of light, extending from the positive wire right through the negative ring. In the rotating mirror a flow was observed towards the negative at very different velocities in different parts of the tube, being much more rapid in the half of the tube nearest the positive.

170.—Pressure 7·023 m.m., 9240 **M**, 7760 cells. Current, when point was positive, 0·02289 **W**, when point was negative, 0·02051 **W**. A photograph on a dry plate, obtained in one minute, showing 17 luminosities, like those in tube 129, at 4 m.m., 5263 **M**, fig. 7, Plate 15, Feb. 1, 1878. On March 14th the luminosities were fifteen in number, whether the point or ring was positive. This tube was detached from the pump, in order to retain this particular phase. It bears a record of the position of the luminosities by a metallic deposit in the cooler spaces between them.

Gassiot Tube 342, *Hydrogen.*

171.—This most interesting tube was a favourite of our friend the late Mr. Gassiot, and was presented by him, with many others, to Mr. Spottiswoode. It retains, in a remarkable degree, the record of old stratification by bands of dark deposit with clear spaces between them. It was a matter of interest to ascertain whether the lines of deposit coincided with the position of the spaces or with that of the strata. This tube is composed of a cylinder 13 inches long and $1\frac{3}{16}$ inch in diameter, having at one end a bulb 2 inches in diameter, from which project at right angles to the main tube two short lengths of tube $1\frac{1}{8}$ inch in diameter, the whole resembling in form the letter T. At the end of the tube opposite the bulb is a straight brass wire $\frac{1}{16}$ inch in diameter screwed on to a wire of platinum, and in the head of the T a brass wire, $4\frac{3}{4}$ inches long, reaching axially right across. The bulb and short tubes attached to it are completely coated with a dense black metallic deposit, and for a space of 5 inches from the bulb the main tube is stained with eight dark bands. 2400 cells gave a current 0·02289 **W**, the straight wire being positive and the cross wire in the bulb negative; there were produced beautiful double strata intensely blue, like those in fig. 3, Plate 16, completely filling the tube. Strips of paper were fastened over these strata in the region of the stains; these were found

to occupy the *unstained spaces*; the stains therefore marked the *intervals*, or cooler parts, between former strata.* The insertion of 500,000 ohms changed the colour of the strata to pink and the form to that shown in fig. 6, Plate 16, but their position remained unaltered. This corroborates our experience with tube 148.

Tube 133, 27 *inches between the terminals, diameter* 1·875 *inch.*

Nitrogen.

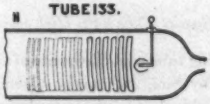
172.—Pressure 10 m.m., 13,158 **M**, 8040 cells. A nebulous light from the positive, extending half the length of the tube to the ring negative.

173.—Pressure 6 m.m., 7895 **M**, 8040 cells. Five steady luminosities, quite uniform, without indications of strata, like 6, fig. 52, but, of course, shorter; with 90,000 ohms gradually introduced the phase continued the same.

174.—Pressure 3·5 m.m., 4605 **M**. 4800 cells would not pass; with 5880 cells, four luminosities.

175.—Pressure 1·5 m.m., 1974 **M**, 3600 cells. Strata near the positive, as fig. 54. These were rather fuzzy, but were better defined with 300,000 ohms introduced.

Fig. 54.



176.—Pressure 1 m.m., 1316 **M**, 3240 cells. Similar strata: with 2,570,000 ohms, six luminosities. The discharge was red throughout the tube, except on the negative terminal, which was violet.

* Gassiot (Brit. Assoc., 1869 (sect.), p. 46): "In one of Geissler's tubes with which I have for some time experimented I obtained, by using my extended series of the voltaic battery, not only a very dense opaque deposit on the glass round the negative electrode, but five or six bands of dark deposit along the tube; in carefully examining their position I find they exactly coincided with the dark band between the striæ, that they did not increase in density by continuing the discharge like the deposit round the negative, but remained without further change.

"I have not any record from Geissler of the nature of the gas, &c., and have not been able to obtain similar results with other tubes obtained from Geissler.

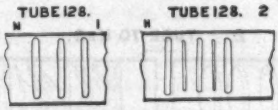
"In one of Cetti's originally charged with arseniuretted hydrogen there was such a deposit.

"This result appeared to me to explain that the deposit in Geissler's tube did not arise from particles of the negative electrode but from the gas with which it was originally charged; their being deposited exactly in the dark portions between the luminous disks may lead to a correct explanation of a phenomenon that has hitherto baffled the ingenuity of the experimentalist."

Tube 128, 25 *inches between the terminals, diameter* 2 *inches.*
*A mixture of Sulphuretted-hydrogen and Hydrogen, the Pressure of the Gas being unknown.**

177.—3240 cells connected with the VARLEY condenser of 42·8 m.f., as in fig. 26, Part I. At the full tension of the battery tongue-shaped strata, as in tube 108, 1, fig. 58; with 200,000 ohms resistance disc-shaped strata were obtained, as 1, fig. 55. When the battery was disconnected from the condenser, and its charge allowed to run down the strata became more distinct, and ultimately a thinner one introduced itself between those already existing, as 2, fig 55. It was also noticed that as the tension fell the strata at first moved *towards the positive*, then became stationary, and afterwards flowed back towards the negative.

Fig. 55.



178.—3600 cells, C. 0·01272 **W**, produced the phase shown in fig. 1, Plate 18, there being a tendency to form tongue-shaped strata. The figure is copied from a photograph obtained in forty seconds. On the insertion of 500,000 ohms resistance, C. 0·00432 **W**, the phase changed to that represented in fig. 2, Plate 18.

179.—With 3240 cells connected with the condenser, as in fig. 26, Part I., the potential of the condenser was measured with the electrometer; when fully charged, tongue-shaped strata were produced; when the potential had fallen to that of 2760 cells the phase shown in fig. 3, Plate 18, was obtained; this is copied from a photograph obtained in 75 seconds.

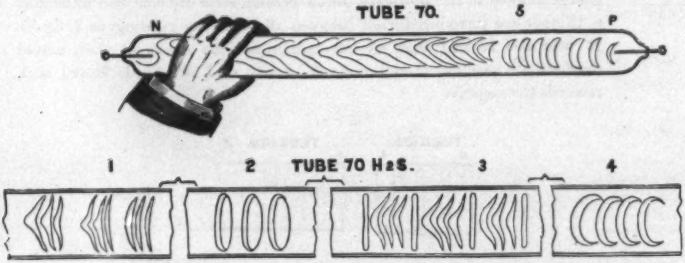
180.—Subsequently a change took place in the tube after standing for six months, when with 2400 rod cells beautiful double strata were produced, the current being 0·01639 **W**. The strata were of a beautiful blue colour with a carmine line between them. A photograph was obtained, but has not been engraved, as it resembles closely fig. 3, Plate 16, except that the double strata only occupied one-half of the tube, the other half towards the negative being a dark discharge.

* In those cases where the pressure is not stated, the tubes were filled and exhausted by the maker; no information being furnished as to the pressure of the residual gas.

-Tube 70, *25 inches between two straight terminals, diameter* 1·875 *inch. Sulphuretted-hydrogen, Pressure not known, the Working Resistance was from* 100,000 *to* 120,000 *ohms.*

181.—With 2160 cells, strata grouped in threes, as 1, fig. 56; on introducing 2,690,000 ohms the disc-shaped strata were produced, shown in 2, fig. 56; with 1,600,000 ohms the strata closed up to half the distance apart and became unsteady.

Fig. 56.



182.—The battery of 2160 cells was connected to the VARLEY condenser of 42·8 m.f., a water resistance of 300,000 ohms being in the circuit. As the charge ran down after the condenser had been disconnected from the battery, a most beautiful series of phases was obtained during the two minutes and a half which elapsed before the potential had fallen so low that the current ceased to pass. The first phase is shown in 3, fig. 56, consisting of groups of three bow-shaped strata with a disc between each group. The next is represented in 4, fig. 56; this was followed by a series of discs, as 1, fig. 55, these gradually became wider apart until there were only eight in the whole length of the tube. The discharge afterwards became a rustling luminosity and suddenly went out. Any phase could be maintained by replenishing the condenser through an adjusted resistance, FR″., fig. 26, Part I.

183.—By frequently working the tube there was gradually deposited a layer of crystalline sulphur on the inside; at last the tongue-shaped strata could no longer be obtained, but it was found that grasping the tube near the negative terminal caused their production, 5, fig. 56. Ultimately the tube became dead and the current of 8040 cells would not pass.

Tube 122, *Sulphuretted Hydrogen and Hydrogen.*

184.—3240 cells connected with the condenser. At full tension a beautiful

steady stratification in groups of three strata, fig. 57, as the tension fell the strata became tongue-shaped and agitated, hugging the tube. As the tension still further fell discs were formed, which gradually became wider apart.

Fig. 57.

Tube 108, 27 *inches long*, 24 *inches between the straight terminals, diameter* 2·375 *inches.*

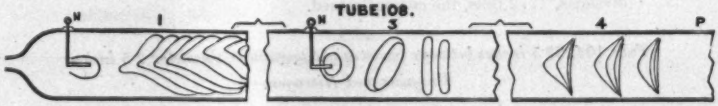
Nitrogen and Bromine.

185.—The battery was connected with the 42·8 m.f. condenser to charge it up fully, and was then disconnected; as the tension ran down, it was measured by means of the electrometer, a charge being taken from the mushroom, fig. 28, Part I., by means of the test plane T.

1080	cells gave a deflection of	24·33	divisions,	=	22·5	per 1000	cells.
2160	,, ,, ,,	51·25	,,	=	23·8	,,	,,
3240	,, ,, ,,	80·75	,,	=	24·9	,,	,,
			Mean		23·7	,,	,,

When the condenser gave a deflection of 50 divisions, = 2109 cells, there were produced, with a resistance in circuit of 1,200,000 ohms, 76 tongue-like strata, as 1, fig. 58.

Fig. 58.



186.—When the potential had fallen to 45 divisions, 1898 cells, with the same external resistance as before, strata, like 3, fig. 58, were produced; the second stratum from the negative was perfectly steady, but the others took up a dancing movement, each splitting into two.

187.—When the potential had fallen to 32 divisions, 1350 cells, still with 1,200,000 ohms resistance, there were fifteen steady strata, as 3, fig. 58; as the tension fell a little lower the stratum nearest the negative turned over,

as represented, and disappeared on the negative. On falling the least degree lower the potential was too small to maintain a current and the tube went out. Although a potential of 1350 cells *kept up* the current it could not be *started* again until the condenser had acquired a much higher one.

188.—On connecting the condenser again with the battery it produced at 70 divisions, 2954 cells, with the same resistance, beautiful double strata, as 4, fig. 58.

189.—The same phenomena as described in 185 were again obtained when the potential had fallen to 42 divisions, 1720 cells. This tube was characterized by the number of the *strata decreasing as the potential fell.*

Tube 105, 27 *inches long,* 24 *inches between the two straight terminals, diameter* 2·25 *inches.*

Cyanogen.

190.—With a potential of 78 divisions, produced by 3240 cells, there were twelve and a half strata.

With a potential of 45 divisions, 1898 cells, 13½ strata.
„ „ 32 „ 1350 „ a rapid flow.
„ „ 28 „ 1181 „ the current ceased.

Tube 106, *about the same dimensions as* 105.

Carbonic Acid and Bromine.

191.—When the potential of the condenser was 70 divisions, 2953 cells, beautiful tongue-shaped strata were produced, which receded from a sheet of tin foil held in the hand and laid on the tube. At a potential of 58 divisions, 2447 cells, a transition took place from tongues to discs; at a potential of 42 divisions, 1772 cells, the current ceased.

Tube 104, 23·5 *inches between two straight terminals, diameter* 2·5 *inches.*

Bromine and Nitrogen.

192.—The same arrangement of condenser of 42·8 m.f., and 3240 cells, 680,000 ohms being introduced in the circuit; at a potential of 65 divisions, 2742 cells, beautiful tongue-shaped strata were produced; at 48 divisions, 1603 cells, the strata became confused; at 35 divisions, 2109 cells the current ceased.

193.—On another occasion, with a battery of 2160 cells, and the same condenser, a resistance of 400,000 ohms being inserted in the circuit, when the electrometer indicated 135 divisions (not of the same value as the preceding), tongue-shaped strata were produced; when the tension had fallen to 110

divisions, 1760 cells, the strata changed to discs, about an inch apart; when it reached 95 divisions, 1520 cells, the current ceased.

Tube 62, 25 *inches between the terminals, diameter* 2 *inches.*
Nitrogen.

194.—2160 cells connected with the 42·8 m.f. condenser, and 400,000 ohms resistance inserted in the circuit, sixteen steady strata which greatly increased in number as the tension fell.

Tube 21, 25·25 *inches between the terminals, diameter* 1·125 *inch.*
Carbonic Acid.

195.—The same arrangement, 3,290,000 ohms; at first with the full potential, only a confused stratification, but as the tension fell it became quite steady, and the phase could be maintained by feeding the condenser through an adjusted resistance FR″, fig. 26, Part I.

Tube 72, 24 *inches between the terminals, diameter* 1·75 *inch.*
Nitrogen.

196.—2160 cells, with the 42·8 m.f. condenser, 1,670,000 ohms resistance in circuit, the resistance of the tube was found to be from 90 to 110 thousand ohms, varying after the current had passed. A most splendid stratification *flowing* majestically *to the positive*, where one stratum vanished after another, but a corresponding one originated near the negative. This phase could be maintained for a very long time by feeding the condenser through an adjusted fluid resistance FR″, fig. 26, Part I. The shape of the strata is shown in fig. 59.

Fig. 59.

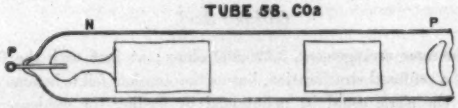
TUBE 72.

Tube 58, 20 *inches between the terminals, diameter* 1·75 *inch.*
Carbonic Acid.

197.—The same arrangement as in 194 as regards the number of cells and condenser, but with 2,690,000 ohms in the circuit. The resistance of the

tube varied from 130,000 to 160,000 ohms. This tube at first gave a beautiful stratification, but after several experiments, it merely showed a tendency to stratification towards the period of cessation of the current. At nearly the full potential one luminosity formed at the positive, a considerable dark interval existing between it and another luminosity which formed in the centre of the tube, and there was a great interval between this and the glow at the negative. As the tension fell, the negative glow became globular, then elongated, and lastly reached the central luminosity; suddenly the central luminosity disappeared, and left a dark interval in its place. This last phase is shown in fig. 60.*

Fig. 60.



Tube 66, *length between the terminals* 28 *inches, diameter* 2 *inches.*
Hydrogen.

198.—The arrangement the same as for 197. With the full potential a splendid phenomenon of 18 steady strata was produced; as the potential fell more strata gradually crowded in from the positive until they reached 43 in number, after which they became confused. With 6,150,000 ohms resistance in circuit there was a rapid flow in which alternating greenish and reddish cross markings were seen; the rotating mirror resolved these into strata alternately pink and greenish. The resistance of the tube was found to be

* Gassiot (Proc. Roy. Soc., vol. xii., 1862-3, p. 336) describes a similar phase: "Depressing the wire very gradually (lessening the resistance) the positive became sharply defined, the negative retaining much of its irregular termination, but each separated by a dark interval of about one inch in length."

Mr. Spottiswoode informs us that at an early stage of his experiments he noticed the formation of large cylindrical blocks of light or luminosities, terminated by flat ends, and separated by dark intervals often as long as themselves. These were most frequently found in tubes from 2 to 3 inches in diameter, containing coal-gas residua, at 0·5 to 0·75 m.m. pressure; they were from 2 to 3 or even 4 inches in length, and sometimes shot out from the positive terminal, then travelled along the tube, and finally disappeared in the dark space towards the negative terminal. They could be produced either by the Holtz machine with a very small air-spark, or with a coil furnished with one of the rapid contact breakers described in a paper (Roy. Soc. Proc. xxiii., 1875, pp. 455–462) referred to above. When observed with a revolving mirror these blocks usually showed striæ in a state of flow. He is of opinion that, at all events when produced under the circumstances here described, these blocks are essentially stratified, and that they are sections of flow, even when the velocity is too great to allow the separate striæ to be detected in the mirror.

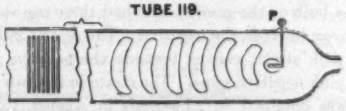
190,000 ohms. This tube was destroyed by the sudden discharge of the condenser before the adoption of the STOKES' safety wire, figs. 69 and 70, and 26, Part I.

Tube 119, *Air.*

199.—This tube had a calibrated chamber connected to it between two stop-cocks, the calibrated portion having a capacity of $\frac{1}{1860}$ part of the tube. With 2160 cells—less would not pass—it produced at a pressure of about 1·5 m.m. 1974 M, a very close stratification, the strata being 0·05 inch apart, as at the left-hand of fig. 61. On letting in $\frac{1}{1860}$ part, by opening the stop-cock connected with the calibrated chamber, the pressure was increased to 2 m.m., 2632 M, and the strata became much wider. The exhaustion was then carried gradually further, until it required 3240 cells to pass, and ultimately 4800; the pressure was so low that we could not then determine it. There were only ten strata produced, as in the right hand of fig. 61, a large dark space intervening between the last stratum and the negative terminal. This tube, unfortunately, cracked near the negative terminal before the contemplated experiments could be completed. This occurred some days after an experiment during which the negative terminal had become overheated.

Fig. 61.

TUBE 119.



When the tube is composed of portions having different bores, the strata vary in *width* and *distance* in the different parts, being narrower and closer in the portions of smaller diameter. This is illustrated by tubes Nos. 18, 26, 51, and 161.

Tube 18, *Nitrogen.*

200.—This tube is represented in fig. 12, Plate 16, copied from a photograph obtained in one minute, August 3rd, 1875, and communicated to the *Académie des Sciences* of Paris.* The dimensions of the tube are as follows: length between the terminals, 32 inches; the horizontal diameter of the left hand ellipsoidal bulb, 4 inches; the tube connecting it with the central bulb, 12 inches; the horizontal diameter of the central bulb, 4·25 inches; the vertical, 5·25 inches; the tube on the right hand of the central bulb, 11 inches; and the horizontal diameter of the bulb on the right, 4·25

* 'Comptes Rendus,' xvi., 686, and xvii., 746, 1875.

inches. The current of 2400 cells was 0·01047 W. The resistance of the tube was found, by substituting wire resistance for it, to amount to 210,000 ohms at the time of the experiment, but several months before it had only a resistance of 18,000. In the small tubes were produced closely-packed strata, in the large central bulb were three umbrella-shaped strata much fainter; these moved towards the negative on introducing 50,000 ohms, a fresh stratum pointed at the apex entering the bulb from the right-hand tube (positive side), C. 0·00672 W. On introducing 20, 20, and 10 more thousand ohms, they retreated from the large bulb *towards the positive*.

Tube 26, *Hydrogen*.

201.—This tube is in form like 10, fig. 37; the length between the terminals 23 inches. The first bulb has a major axis, 3·25 inches, a minor, 1·875 inch, the tube joining this with the central bulb, 6 inches long, its internal diameter 0·44 inch; the central bulb has a horizontal major axis, 4·5 inches, the minor being 2·25 inches; the tube joining it to the third bulb is 5·5 long, its internal diameter 0·56 inch; the major axis of the third bulb, 3·5 inches, the minor, 2·125 inches. With 3240 cells, when the small tube was positive, C. 0·0073; when negative, 0·00481 W. When the small tube was either positive or negative it had 34 strata, while the large tube had had 25. The bulb on the positive side had three cup-shaped strata near the terminal, convex towards the negative. The central bulb had also three or four fainter pink strata, convex towards the negative; the third bulb was filled with a pink negative glow. The strata in the two tubes were blue. A photograph was obtained in 25 seconds in August, 1875, but has not been engraved, and is another of those communicated to the *Académie des Sciences* of Paris.

Tube 51, *Hydrogen*.

201*a*.—This tube was constructed to show that the extent of the glow along the negative terminal was dependent on the strength of the current. The length of the tube is 6 inches, the diameter 2 inches. The negative terminal is a platinum wire 19 inches long, and about 0·025 inch in diameter, coiled into a horizontal spiral of four complete turns, concentric with the tube; it is supported in its position by three fine glass rods running parallel to the axis of the tube. The positive terminal is straight, and extends vertically to the common axis of the tube and spiral. The distance between the last ring of the spiral and the positive terminal is $\frac{3}{8}$ inch. As the strength of the current is increased, the glow which, with a current of 0·00238 W, illuminates only the 2 inches of the negative nearest

to the positive, spreads backwards until, with a current of 0·01575 W, it covers the whole terminal. The following are the observations of the lengths of wire illuminated which correspond to the various strengths of currents with 1200 cells :—

Currents.	0·00238	0·00263	0·00277	0·00347	0·00555	0·01023	0·01158	0·01575 Weber.
Lengths.	2	2·5	4·5	7	9	13·5	15·75	19 Inches.

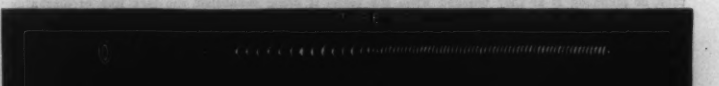
Tube 161, *Hydrogen.*

202.—The difference of the strata in tubes of different diameter* at the same pressure and with the same current is very clearly brought out in tube 161, composed of two portions, one being 18 inches long and 1·65 inch internal diameter, the other 17·5 inches long and 0·975 inch diameter, the ratio of the sectional areas being 2·864 to 1. The terminal in the small tube is a point, in the large one a ring. With 4800 cells, the point (small tube) positive C. 0·02825 W, there were produced in the small tube 62 disc-shaped strata, and in the large tube twelve saucer-shaped strata occupying half of the length of the large tube; beyond these the discharge was dark. With the point negative, C. 0·02451, there were produced in the small tube 54 discs, and in the large tube thirteen saucer-shaped, completely filling it. The number of strata does not therefore appear to be in the inverse ratio of the areas. The strata in the small tube were blue, but at times, with a large current, carmine, as in the capillary part of a spectrum-analysis tube, the strata in the large tube being much fainter and pink. The appearance when the point was positive

Fig. 62.

TUBE 161.

Fig. 62a.



* Spottiswoode (Proc. Roy. Soc., xxv., 1876–77, p. 79) describes an experiment "on a hydrogen tube of conical form the diameter of which varied from capillary size to ½ inch, the capillary end being at the bottom, the positive terminal at the top. The principal interest of this tube consists in showing the influence of diameter upon the velocity of proper motion. The wider the tube the freer, it seems, the striæ are to move."

is shown in the diagram, fig. 62. Fig. 62a and 62b, copied from photographs obtained, the former in 15 seconds, the latter in 10 seconds, show respectively the appearances at another phase, when the small tube was positive or negative respectively.

Spottiswoode *Tube* 147, *with a Shifting Terminal.* *Carbonic Acid.*

203.—It will be seen on reading the foregoing histories, especially those of tubes 129, 139, 130, that the strata all take their origin at the positive terminal, and that first one, then two, three, and so on, make their appearance as the pressure of the gas is diminished. A glance at Plate 15 will render this evident, all the strata having their origin at the positive terminal. But Mr. Spottiswoode's elegant contrivance of a moveable terminal shows this to be the case in the most conclusive manner; * we give in Plate 17, figs. *a*, *b*, *c*, *d*, *e*, *f*, *g*, *h*, a representation of the strata obtained, in eight different positions of the terminal, in a tube we had made after his model by his permission; it is 56 inches long and 1·375 inch diameter, and is shown in figs. 39 and 40, page 164. Plate 17 does not give the first phase—a single stratum—formed on the positive terminal a certain distance from the negative, *which distance remains constant*, as is shown in the plate. 3240 powder cells were used with a resistance of 200,000 ohms to produce a steady discharge.

* Gassiot (Phil. Trans., 1858, p. 12) used a tube attached to a mercurial cistern which was connected with an air-pump; as the pressure was reduced in this cistern, mercury, which originally filled the tube supported in a vertical direction, descended, producing a Torricellian vacuum of less or greater length. The surface of the mercury acted as the negative terminal. He says:—

"It is curious to observe the stratifications retreating from the negative as the mercury ascends the tube, or following it as they descend when the vessel is being exhausted, the dark line of discharge being compressed or expanded in proportion as the length of the stratification is increased or decreased."

Also in speaking of the stratified discharge as affected by a moveable glass ball (Brit. Ass. Aberdeen, vol. xxix., 1859, sect. p. 11), he says:—

"I have already stated that the stratifications near the positive wire are indistinct; but if the glass bead is placed near the positive wire and then allowed slowly to descend towards the negative, the stratifications at the positive are at first clearly defined near that terminal as at the negative, and as the bead rolls gently down, they have the appearance of following the bead and issuing one after the other from the positive wire until the bead reaches to within a few inches of the negative, when this action gradually ceases. If the tube is now inclined so as to allow the glass bead to return in the contrary direction the stratifications appear to recede, becoming more and more clearly defined, until the bead passes the positive terminal wire, when the entire discharge returns to its normal state."

Photograph.	Distances between terminals. inches.	Ratio of distance.	Current W.	Ratio of current.
a	7	1·00	0·00912	1·29
b	13	1·86	0·00858	1·22
c	19	2·71	0·00858	1·22
d	25	3·57	0·00807	1·14
e	31	4·43	0·00834	1·18
f	37	5·29	0·00782	1·11
g	43	6·14	0·00756	1·07
h	49	7·00	0·00706	1·00

The representations given in Plate 17 show the number of strata in each case; they are copied from photographs obtained in succession. The resistances of the tube for the several distances between the terminals are given in page 164. When the primary of coil 819 was in circuit, as fig. 69, page 227, the advent or retreat of a stratum produced a deflection of the galvanometer in connexion with the secondary of the coil, thus indicating a pulsation in the current.

We have already stated * that the discharge is frequently flowing and unsteady, but that *perfectly steady strata may be produced by properly regulating the current* by the gradual introduction of resistance in the circuit.† In Plate 17 we give three cases by way of example, thus :—

Tube 73, 22·5 *inches between the two straight terminals, diameter* 1·5 *inch*, C_2H_6.

204.—4800 cells, C. 0·00731 W, produced an agitated discharge throughout almost the whole length of the tube, there being only four strata, as shown in fig. 2, *a*, Plate 17. By the introduction of 200,000 ohms the current was reduced to 0·000408 W, and then perfectly steady strata were produced, as in *b* of the same figure. These are copied from photographs obtained in 20 and 30 seconds respectively.

* 'Comptes Rendus,' xvi., 686, and xvii., 746, 1875.

Quet ('Comptes Rendus', xxxv., 949–952) tried by shifting the positive terminal to drive it into the dark space near the negative. He found he could extinguish the positive light in air at atmospheric pressure, but not in rarefied gas.

† Gassiot (Proc. Roy. Soc. 1872–3, p. 388): "No. 248. The discharge under certain conditions is continuous and under others it becomes intermittent. These conditions are, that without resistance introduced in the circuit, except that inherent in the battery, the discharge cannot be resolved by the rotating mirror, and so far must be considered continuous, but when a certain given and described resistance is introduced in the circuit the discharge becomes intermittent."

And at p. 339: "The form in figuration of the striæ and the positions they occupy in the vacuum tube appear to depend on two separate and distinct conditions, 1st, the power and energy of the battery; 2nd, the state of tension of the highly attenuated matter through which the discharge is visible."

"The striæ can be controlled, their number increased or reduced, and their places or positions in the tubes altered by the introduction of measurable amounts of resistance in circuit."

Tube 106, 23·5 *inches between the two straight terminals composed of wire about* 0·25 *inch thick, diameter* 2 *inches.*

Carbonic Acid and Bromine.

205.—4800 cells, C. 0·01840 W. A confused discharge throughout, as fig. 4, *a*, Plate 17. With 1,770,000 ohms the current reduced to 0·00238 W, when strata were produced, filling about half of tube as *b* in the same figure. These are copied from photographs obtained in 90 seconds and 4 minutes respectively.

In illustration of the *change in the number of strata produced by a variation in the current* we give a few more examples besides those already mentioned.

Tube 111, 23 *inches between the straight terminals, diameter* 2·25 *inches.*

Cyanogen.

206.—4800 cells, C. 0·01272 W. Seven strata as shown in fig. 3, *a*, Plate 17, which is copied from a photograph obtained in 15 seconds. The introduction of 1,000,000 ohms reduced the current to 0·00383 W, and then ten strata were obtained, as shown in *b* of the same figure, from a photograph obtained in 60 seconds.

Tube 105, 25 *inches between the straight terminals, diameter* 2 *inches.*

Cyanogen.

207.—3600 cells, C. 0·00834 W. Ten strata were produced, as shown in fig. 7, *a*, Plate 17, copied from a photograph obtained in 20 seconds. The introduction of 700,000 ohms reduced the current to 0·00191 W, and then there were thirteen strata, as shown in *b* of the same figure, from a photograph obtained in one minute.

In both the foregoing cases, tubes 111 and 105, *the strata increased in number with the decrease of current.*

Tube 124, 26 *inches between the straight terminals, diameter* 2 *inches.*

Sulphurous Acid.

208.—3240 cells in connexion with the condenser, as shown in fig. 26, Part I. At the full potential 29 strata were produced, as shown in fig. 4, Plate 18, copied from a photograph obtained in 12 seconds in the presence of their Excellencies Kuo Sung tao, Minister of China, and Lien Hsi-hung, Assistant-Minister, April 27th, 1877. On introducing 1,000,000 ohms, the number

was reduced to 27, and just before the current ceased to pass after the battery had been disconnected from the condenser the number fell to 21.

In the case of tube 124 *the strata decreased in number with the decrease of current.*

The introduction of any substance in the tube, such as rings or flags of metal, produces an interruption of strata very much as if they acted as distinct terminals.

Tube 120, *Carbonic Acid.*

209.—This tube is 28 inches long between the end straight terminals, and 1·75 inch diameter, with two lightly suspended aluminium flags. Nine strata produced from the positive, then a dark space between them and the first flag, which is brightly illuminated. This seemed to act as a fresh terminal, from which started ten strata, beyond which there was again a dark space between them and the second flag, which in its turn appeared to act as a new terminal, being illuminated by a glow.* Five other strata were formed on the other side of this, and beyond them there was a dark space, and the negative terminal was brilliantly illuminated. Fig. 5, Plate 17, copied from a photograph shows the phenomena; no motion of the flags could be detected during the passage of the current, 0·01158 W.

Tube 101, *Carbonic Acid.*

210.—This tube is 25 inches long between two straight terminals, and 1·5 inch in diameter; beginning at the positive terminal on the right, at 1·25 inch is a fixed flag 0·5 inch square, beyond this at 1·5 inch another, at the middle of the tube a ring 1 inch in diameter; on either side of this ring at 1·375 inch distance are two balls about 0·375 inch in diameter, then two other square fixed flags at the same distances from the left hand (negative) terminal and from each other. It will be seen by referring to fig. 6, Plate 17, that a close stratified discharge is shown with an illumination of each of the impediments except the last two flags near the negative, as in tubes referred to at page 165. This figure is copied from a photograph taken when the tube was connected with 2400 cells and 150,000 ohms resistance, C. 0·00504 W.

* Gaugain ('Comptes Rendus,' xli., 1855, pp. 152–156) compares the behaviour of gases in this respect with that of liquid electrolytes where the introduction of a metal diaphragm between the electrodes increases the resistance, and the two faces of the diaphragm act as opposite electrodes. Gaugain further remarks that if the metal obstruction be pierced it ceases to act as a double electrode in gases, a fact confirmed by our many experiments with tubes furnished with metal rings (fig. 41, p. 165).

In the preceding pages it has been shown that the number of strata varies with the pressure of the gas, beginning with one luminosity, then increasing in number up to a certain point as the pressure is diminished; as the gas becomes gradually attenuated the strata become thicker and fewer; lastly, the current passes with increasing difficulty, and the strata have a tendency to run together. With the mercurial pump alone we have not been able to obtain a lower pressure than 2·6 **M**, but with the employment of spongy palladium in a hydrogen vacuum we have reduced the pressure to 0·000055 m.m., 0·066 **M**.

Tube 145, *Hydrogen.*

Length 25 *inches,* 20 *inches between the terminals, one a wire, the other a ring, diameter* $1\frac{3}{8}$ *inch.*

This tube is represented at 145, fig. 37. It has an absorption chamber containing spongy palladium, obtained by heating its cyanide to redness; this chamber is $5\frac{1}{2}$ inches long, $\frac{3}{8}$ inch in diameter, and is about half-full of palladium, which is held in its place by plugs of palladium-foil. At one end of the tube is a short capillary calibrated tube contained between two glass stop-cocks, the first communicating with the tube, the second with the hydrogen generator.

The tube was repeatedly exhausted and filled with dry hydrogen, while the absorption chamber was being heated in a copper air-bath to a temperature above the range of the mercurial thermometer; a double saddle-screen of tinned iron, placed on the small tube connecting the absorption chamber with the glass cock, effectually protected the latter from excessive heat. At various pressures from 35 m.m., 46,053 **M**,* at which the current of 11,000 cells just passed where the ring was positive, most of the phenomena recorded for tube 129 were obtained, but the following are the experiments for which the tube was specially constructed.

In the first instance, in order to test the absorbing power of the palladium, it was heated for some hours, and the tube was very completely exhausted; it was then filled with hydrogen at the atmospheric pressure, and kept at this pressure while the palladium cooled. The tube was exhausted again, and it was found that at 10 m.m. the palladium gave off hydrogen sensibly at ordinary temperatures; then the air-bath was heated above the range of the mercurial thermometer, when the gas filled the

* Morren, A. ('Comptes Rendus,' liv., 1862, p. 736) states that he obtained a current in hydrogen at a pressure of 24 m.m., which caused a deviation of 1° of his galvanometer; at a pressure of 2·8 m.m. the deviation was at a maximum 46°, and at 0·06 m.m. the current was less, the deviation being 30°. He gives the currents also in carbonic anhydride, nitrogen, and carbonic oxide. In the Ann. de Chim., iv., 1865, pp. 320–352, is an elaborate investigation on the electric conductibility of gases at very low pressures, by this author, the pressure of the gas being estimated by allowing a known volume of gas to enter a tube of known capacity in which had been produced a torricellian vacuum; he found (p. 338) the transmission of electricity to cease at a pressure of 0·0037 m.m. with nitrogen.

tube, both pumps, and the McLEOD gauge to a pressure of 410 m.m., 539474 **M**, thus showing that it was capable of absorbing a large volume of gas.

211.—The tube was now exhausted, first with the ALVERGNIAT pump, which was subsequently shut off at the cock C, fig. 35, afterwards with the SPRENGEL, the cock between the absorption chamber and the tube being left open.

When the pressure had reached 0·005 m.m., 6·58 **M**, the current of 11,000 cells would pass only when the straight wire was negative. When the pressure was 0·00137 m.m., 1·8 **M**, the current would not pass in either direction. The exhaustion and absorption were carried on until the pressure fell to 0·000055 m.m., 0·066 **M**, at which pressure there was, of course, no current. The APPS's induction coil 821, set to produce a 1-inch spark, would not pass at first, but did so after the current had been made to pass with a 6-inch spark. The pressure rose to 0·0024 m.m., 3·2 **M**.

212.—Exhaustion to 0·00016 m.m., 0·2 **M**, having been again obtained, the absorption chamber was shut off, and a charge of gas from the calibrated tube, the capacity of which is $\frac{1}{1100}$ that of the main tube, was let into the tube and SPRENGEL pump; it increased the pressure to 0·226 m.m., giving $\frac{1}{1400}$ for the ratio of the capacity of the calibrated chamber to that of the tube plus the SPRENGEL pump and McLEOD gauge. When the gas was let in the current of 11,000 cells, 0·04201 **W**, immediately flashed through the tube, and produced twenty blue strata, like those in fig. 9, Plate 16, reaching to within 7 inches of the negative. 1200 cells gave a current 0·00580 **W**, and produced nineteen grey strata, the concave face of that nearest the negative being pink.

213.—The absorption chamber was now opened, and in about five minutes the pressure was reduced to 0·0268 m.m., 35 **M**. 11,000 cells, C. 0·01102 **W**, produced nine milky broad strata, like those in fig. 12, Plate 16. In 45 minutes the pressure had decreased to 0·00137 m.m., 1·8 **M**, and 11,000 cells would not pass.

214.—Two charges let in; pressure 0·435 m.m., 571 **M**, 1200 cells, C. 0·00993 **W**, twenty-two pink strata as fig. 5, Plate 16; 2400 cells, C. 0·02634 **W**, rendered the strata blue, and like fig. 4 of the same Plate.

215.—Third charge, pressure 0·6423 m.m., 844 **M**, 2400 cells, C. 0·02776 **W**.

216.—Fourth charge, pressure 0·8968 m.m., 1180 **M**, 2400 cells, C. 0·02925 **W**. twenty-four blue strata, like fig. 4, Plate 16.

217.—Fifth charge, pressure 1·1294 m.m., 1486 **M**, 2400 cells, C. 0·02925 **W**, twenty-two blue and very deep cup-shaped strata.

218.—Sixth charge, pressure 1·396 m.m., 1836 **M**, 2400 cells, C. 0·02850 **W**. An agitated stratification of tongues crossing each other and producing a kind of × form. The C and F lines, which had been faint in the other phases, were bright in the negative glow, but not in a stratum.

219.—Seventh charge, pressure 1·6656 m.m., 2191 **M**, 1200 cells would not pass; 2400 cells, C. 0·02728 **W**. The cup-shaped strata became longer, and curved at the end, reminding one of a Phrygian cap.

220.—Eighth charge, pressure 1·9265 m.m., 2534 **M**, 2400 cells, C. 0·02728 **W**; only a confused discharge. 3600 cells, C. 0·03620 **W**; very deep cup-shaped steady blue strata, as deep as those in fig. 7, Plate 16, but not, like them, tongue-shaped. C, F, and G lines visible with spectroscope.

221.—The absorption chamber was now connected with the tube. With 3600 cells, phenomena in the reverse order were obtained. The pressure was observed to have fallen in a few minutes to 1·003 m.m., 1318 **M**; in 10 minutes to 0·1245 m.m., 164 **M**; and in 45 minutes to 0·0217 m.m., 28 **M**, when it required 4800, and subsequently 6300 cells to pass. At first when the saucer-shaped strata had disappeared, twenty-one disc-shaped strata presented themselves; these widened out, and there were successively sixteen, fourteen, and twelve, becoming like figs. 8, 9, 11, and 12, Plate 16, respectively. When the two last phases were produced, the hydrogen lines could not be seen either in the strata or the glow on the negative ring, but, instead of them, mercury lines came out strongly.* There is reason to think that at this stage there was little gas, except mercury vapour, in the tube.

It is to be observed that, with a very high degree of exhaustion, the tongue-, and saucer-shaped strata are no longer produced in a hydrogen vacuum, and that the strata assume the disc-form usual with carbonic acid, air, and nitrogen.

Tube 81, 25·5 *inches between the terminals, diameter* 0·875 *inch.*
Carbonic Acid.

222.—This tube is connected with a smaller one containing a stick of potash, see 81, fig. 37.† The current of 11,000 cells will only just flash across in one direction after the tube has remained at rest for some months so as to allow of the complete action of the potash. On heating the potash bulb gas is given off, and then the current of 2160 is sufficient, the maximum current with this battery being 0·00238 **W**. On heating the bulb still more it required 3240 cells to pass, and ultimately this was insufficient; by allowing the potash bulb again to cool the current of 3240 cells passed, and very close strata were produced, nine in an inch; then, as it still further

* Hittorf (Pogg. Ann. cxxxvi., 1869, pp. 1–31) measured the quantity of mercury vapour from his pump absorbed by a silver surface. He found it amounted in certain circumstances to 0·25 milligramme per square centimetre per diem. Morren (Ann. de Chim. iv., 1864–5, pp. 325–352) describes the difficulties he encountered from the presence of the mercury vapour as well as of other gases which he believes are usually dissolved in mercury.

† Gassiot describes experiments with such a tube, Roy. Soc. Proc. x., 1860, p. 402.

cooled, the vacuum becoming better, seven, six, and so on to two in an inch were produced; lastly, before the current ceased to pass, the strata rapidly widened out, *flowing towards the positive.*

Tube 9, *Hydrogen.*

223.—This is a tube with a diaphragm of glass having a hole in it 0·25 inch diameter, the length between the terminals being 11 inches; it also has a potash chamber for the complete absorption of moisture, 9, fig. 37; with 2160 cells, the potash chamber having been previously heated, about three strata were produced in the compartment near the positive; as the chamber cooled and the vacuum became more perfect, six strata formed in this compartment, completely filling it, and one after the other appeared to squeeze through the small hole in the diaphragm into the negative compartment, where two strata formed, each double, like those in fig. 3, Plate 16.

Tube 116.

224.—This is one of the so-called induction tubes, like, in some respects, that shown in 19, fig. 37; it consists, however, of three chambers, the distance between the terminals being 37 inches. It is composed of a large central tube 18·5 inches long, 2·25 inches diameter, terminating at each end in a bulb 2·5 inches in diameter, and containing carbonic acid. Enclosed in these bulbs are two smaller bulbs 2·125 inches in diameter, connected each with a spheroidal bulb, the major axis of which is 3·375, and the minor 2·5 inches; these contain nitrogen. In these spheroids the terminals are placed, so that each is enclosed in a separate chamber (see Plate 18, fig. 5). On connecting this tube with 6960 cells a flash is perceived in the several compartments of the tubes; on reversing the current another flash, but no continuous illumination as with the induction coil. As in an induction coil there is a series of rapid reversals of current, it is evident that it illuminates induction tubes by an alternate charging up and discharge of the leyden jars formed by the contained bulbs, on each side of which is residual gas, which acts as the carrier of electricity. By rapidly reversing the current of the battery by means of the key, figs. 2 and 3, page 59, Part I., the tube becomes illuminated, but not so well as with an induction coil. On, however, employing the rapid commutator shown in fig. 8, Part I., which alternates the current 352 times or less in a second, a most splendid illumination of the tube takes place, producing an appearance shown in fig. 5, Plate 18, copied partly from a photograph obtained when 6960 cells were used and with about 150 reversals of current in a second. The two spheroidal chambers communicating with the enclosed globes became illuminated

with pink and red streamers, and the long central tube with olive grey strata, apparently convex in both directions, but which the rotating mirror separated into two components, one convex in one direction, the other in the other. In the photograph only a continuous light is seen in the central tube, so that the detail, there shown, is from eye observation.

Sensitiveness to External Influence.

225.—In the preceding description we have alluded to the sensitiveness of tubes to the approach of the hand, or touch of the finger; the tube shown in fig. 63, containing cyanogen, is an example of an extreme case: it gave tongue-shaped strata, and these entirely disappeared on the touch of a finger, all the tongues running into a continuous wave-discharge constricted near the finger.

Fig. 63.

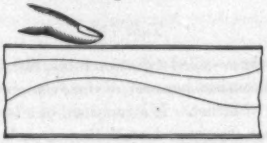
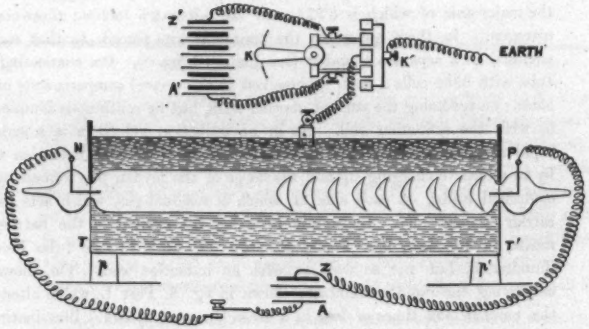


Fig. 64.



An endeavour was made on the suggestion of Professor STOKES to throw some light on the effect of external influence on the character of the strata, in the manner shown in fig. 64.

Tube No. 8, 14 *inches long, diameter* 1·5 *inch.*

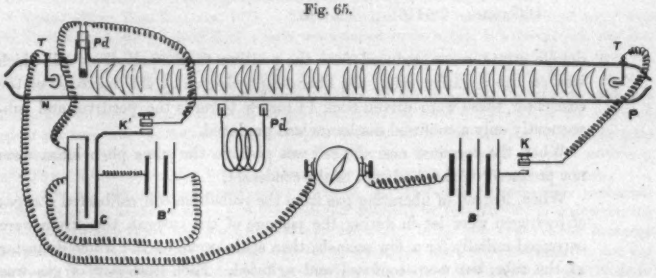
226.—This tube was placed in a metallic trough, 15 inches long, 4·5 inches deep, and the same wide; the trough was insulated on four paraffin cylinders $p\ p'$, and filled with water, and also with a solution of common salt. The resistance of the tube was 60,000 ohms, 1200 cells would pass, but 2400 were used with a resistance of 200,000 ohms, giving eight strata, C. 0·00259 W. On connecting one pole of the battery, and one terminal of the tube to earth, and the other pole to the other terminal of the tube, it was found that the difference of potential between the two terminals of the tube was the same, 1131 volts, whether the tube was in air, water, or a solution of common salt, and whether the trough was insulated or connected to earth.

The experiment was repeated, but with the addition of the employment of a second battery A′ Z′ of 3240 cells, which was used to charge up the trough alternately + or − whilst the current of a battery of 1460 cells passed continuously through the tube. At each reversal of the charge of the liquid in the trough, a flash of light passed through the whole length of the tube, and the strata made a slight movement towards the negative terminal and back again to their original position. It was thought that the discharge, under the influence of induction, might take a hollow cylindrical form, but this did not occur.

Tube 160, *Hydrogen.*

227.—This tube was constructed with the object of sending the analogue of a smoke ring through a tube in which a steady stratification had been procured and sustained: fig. 65 shows the arrangement.

Fig. 65.



The tube is 40 inches long and 1·875 inch in diameter, and has a stop cock

at each end; near one of the ends is a small tube, 0·75 inch in diameter, fastened to the main tube at right angles, and fitted with a glass stopper, in which two stout platinum wires, 0·043 inch diameter, are melted; there is soldered, with gold, to the two platinum wires a spiral of palladium made of wire 12 inches long and 0·0125 inch diameter, P*d*, in the diagram. The palladium coil was charged to saturation with hydrogen, by immersing it in dilute sulphuric acid and making it the negative pole of a bichromate battery of six elements; after it had been washed in distilled water it was dried and inserted in the tube. The two stout wires of platinum, to which the palladium coil is attached, are connected to a condenser of 10·9 m.f., charged with 3240 cells. One of the wires leads to K′ so that no current can pass from the condenser until this key is pressed down, when this is done the charge passes and by suddenly igniting the wire drives off the hydrogen.

On first making the experiment, through inadvertence, the condenser was not connected with the palladium coil, but the current in the tube heated it and drove off the hydrogen, producing the effect to be described. Pressure 1·003 m.m., 1320 **M**, 5120 cells, 300,000 ohms resistance, saucer-shaped strata as shown in the diagram. As soon as the palladium coil became heated it suddenly drove back the strata about one-third the length of the tube from the negative, and the current subsequently became agitated. After the liberation of the gas the pressure was increased to 1·088 m.m., 1432 **M** or by 112 **M**, the pressure before and after discharge being as 1 to 1·08.

This experiment was repeated with 4800 cells without external resistance,

Pressure 0·9965 m.m., before the discharge of the condenser,
„ 1·0381 „ after „ „ „

Difference 0·0416 „ 55 **M**,

double strata were produced from the positive to the palladium coil which was on the negative side. On liberating hydrogen by the discharge of the condenser these were driven back 14 inches towards the positive, and subsequently only a confused discharge was produced.

When the terminal near the coil was positive the same phenomena were not produced on the discharge of the condenser.

When, instead of liberating gas from the palladium coil, calibarted charges of hydrogen were let in during the passage of the current, the strata were narrowed radially for a few seconds, then again occupied the whole diameter of the tube, but were confused and agitated. Each fresh puff of gas was accompanied by a fresh radial collapse, and, at the same time, by a repulsion

of the strata from the negative, whether the puff of gas entered from the negative or from the positive end.*

The wires of this tube had been enclosed nearly up to their extremities in capillary glass tubes; after repeated discharges these tubes fuzed and enclosed the wires nearly completely, only leaving a section of them free. When this had happened a very striking phenomenon was observed at the negative terminal on sending a current of 5120 cells through the tube, numerous sparks were thrown off from the extremity of the wire in a very thin sheet at right angles to the axis of the tube, producing the appearance of spokes of a wheel; the discharge throughout the tube was not stratified. Not the slightest projection occurred either backwards or forwards in the direction of the length of the tube, showing that there is a lateral force existing at the negative terminal. The axial direction of the positive impulse, combined with the radial direction of the negative, at right angles to it, may play an important part in the production of stratification.†

* De la Rive (Genève Mém. Soc. Phys. xvii., 1863, p. 75) made similar experiments; he introduced during the passage of a current in a vacuum a charge of the same gas that it contained, in quantities sufficient to lower the column of mercury $\frac{1}{2}$ or $\frac{1}{4}$ a millimetre. If the gas were introduced at the negative end striæ well defined were immediately formed in the dark space of the same diameter (that of the tube) as the striæ already existing, but much closer and narrower. These gradually extended the whole length of the tube, entangling the original striæ in their course. When the admission of gas had been stopped the luminous column gradually receded from the negative and the tube took up its normal appearance. If the gas were introduced at the positive end, instead of striæ occupying the whole length of the tube *a narrow jet* of brilliant light was seen to advance along the axis of the tube in the interior of the luminous column, which immediately extended through the dark space near the negative. When the admission of gas had ceased the tube returned to its normal condition. In the same paper (pp. 73–74) the author describes some experiments in which he had a gauge attached to the vacuum tube: the mercury column was observed to oscillate during the discharge through a range of, under favourable circumstances, 0·4 m.m.; De la Rive considers that these two experiments support the opinion of Reiss, of Bérlin, that these phenomena are purely mechanical.

Spottiswoode showed a similar experiment at a recent meeting of the Royal Society.

† Varley (Proc. Roy. Soc., xix., 1871, p. 239) constructed a tube in which a slip of talc, 1 inch long, $\frac{1}{16}$ inch broad, and weighing $\frac{1}{10}$ of a grain, was attached in the middle to a fibre of silk stretched diametrically across the tube; the position of the vane was not between the terminals, two rings, but between one end of the tube and one of them. When the discharge, which was in the form of an arch, passed between the two terminals no effect was produced on the vane; when, however, the arch was influenced by an electro-magnet and made to play upon either the lower or upper end of the vane that part of the vane was repelled, no matter in which direction the current was passing, in some cases as much as 20°. The author states that in his opinion the arch is composed of *attenuated particles of matter projected* from the negative pole in all directions, but that the magnet controls their course.

The view that the striæ are aggregations of matter, and that their formation is a mechanical process, appears to receive some support from the fact described by Spottiswoode in a paper on the rapid-contact-breaker (Proc. Roy. Soc. xxiii., 1875, pp. 445–462). In the case of the double discharge the striæ of the one discharge fit exactly into the spaces of the other, indicating thereby that the distribution of the residual gas at the close of one discharge is such as to favour a similar distribution in an immediately succeeding discharge, and that time is necessary for a fresh distribution.

See also Appendix, note C.

The two tubes about to be described present some very remarkable phenomena, which show that the terminals in some cases are able to absorb the gases of the vacuum tubes and to give them off again under the influence of the current.

Tube 48, *length* 7 *inches, between the terminals* $2\frac{3}{4}$ *inches, diameter* $1\frac{1}{4}$ *inch.*

228.—The residual gas is hydrogen, the negative terminal a spiral, the positive a straight wire, both of palladium 0·05 inch diameter; with 1200 cells, C. 0·01331 W, with 2400 cells, C. 0·02371 W; in the latter case the deflection of the galvanometer was reproduced by 40,000 ohms inserted in the circuit in lieu of the tube.

Both wires before the experiment were bright and metallic; there were produced six strata at the positive and a glow around the negative, a copious mirror-like translucent deposit forming on the tube about the negative, which, examined by the microscope with a power of 260–570 linear, appeared to consist of cubes or four-sided prisms $\frac{1}{3500}$ inch across. If the current was continued for about a minute a central zone was cleared by the heat and the deposit carried further along the tube. Gradually there was formed a similar deposit, but not so dense, on the tube round the positive terminal. The curious part of the phenomenon is that the negative and positive terminals, having become mat and black as if covered with a deposit of spongy palladium, resume their metallic appearance on laying the tube aside for a week or two; in the mean time the deposit is entirely re-absorbed by the terminals, which become white like frosted silver, and the glass is left quite clear. This experiment has been repeated very many times with the same result. Is the deposit a definite compound of palladium and hydrogen? *

Tube 49, *length* 9 *inches, between the terminals* $3\frac{1}{2}$ *inches, diameter* $1\frac{3}{4}$ *inch.*

229.—The residual gas hydrogen, the negative terminal a spiral of palladium, the positive an aluminium wire; 2400 cells, C. 0·01982 W; the resistance reproduced by 70,000 ohms. Similar phenomena were produced, except that around the positive terminal, the aluminium wire, there was no deposit.

We have made several experiments with tubes containing other gases besides those already mentioned, for example:—hydrochloric, HCl, hydrobromic, HBr, and hydrofluosilic, $4HF,SiF_4$, acids; carbonic oxide, CO, olefiant gas, C_2H_4; phosphoretted hydrogen, PH_3; arsenetted hydrogen, AsH_3; dioxide of nitrogen, N_2O_2. But we have nothing special to mention at present with respect to them, and they all require a more extended study.

* Graham, 'Chemical and Physical Researches,' collected by Angus Smith, 1876, pp. 281–299. Troost and Hautefeuille, 'Comptes Rendus,' lxxviii. pp. 686–690, describe a compound Pd_2H.

Throughout our researches we have not seen in a carbonic acid vacuum any umbrella-, saucer-, or tongue-shaped strata as shown in Plate 11, figs. 2, 6, and 7, respectively; so far as our experience goes they are always of the disc-form shown in figs. 8, 9, 10, 11, 12, Plate 16, and fig. 1*h* in Plate 17.

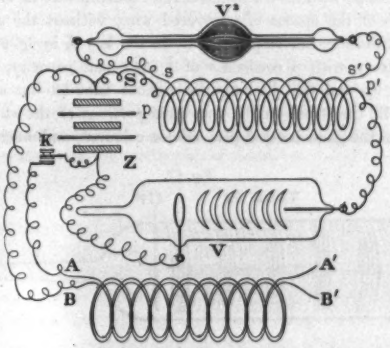
On the other hand, hydrogen, phosphoretted hydrogen, and arsenetted hydrogen will give the umbrella-, saucer-, and tongue-like strata.

Some tubes containing sulphurous acid give these forms of strata, while cyanogen gives the disc-shaped as in carbonic acid.

Tubes prepared by Dr. GEISSLER containing a mixture of gases, such as phosphoretted hydrogen and hydrogen, carbonic acid and bromine, nitrogen and bromine, as a rule give a most beautiful stratification and point to the desirability of a more extended study of the effect of mixture of gases on the electric discharge.

In 1875 we made a communication to the Royal Society, in connexion with our friend Mr. SPOTTISWOODE, on Electrical Discharges in Vacuo,* in which were described some phenomena bearing on the cause of stratification in vacuum tubes; we have recently repeated the experiments obtaining the same phenomena, and we have, this time, recorded them by photography, as shown in Plate 18, fig. 6, *a* and *b*, fig. 7, *a* and *b*, and fig. 8, *a* and *b*. The diagram, fig. 66, exhibits the arrangement of the

Fig. 66.



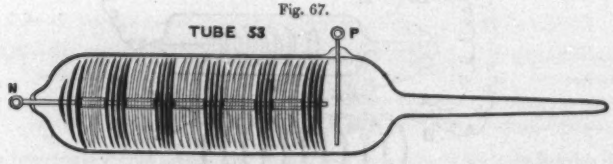
apparatus; S Z, a battery of 1080 cells connected at one terminal, S, to the primary of an induction coil P P′, thence to the straight wire of the vacuum tube V, the other, a ring in this case, being connected to the Z terminal of the battery; the positive current consequently passed from S through P P′, and through the tube V. The secondary wire S S′ of the induction coil was connected to a tell-tale tube V². Under

* Proc. Roy. Soc., vol. xxiii. p. 356, 1875.

the circumstances just described, it will be remembered that a nebulous discharge occurred in V without stratification, and that no illumination of the tell-tale tube took place. The battery was also connected at the S terminal, without any intervening resistance, to one side A A′ of a condenser, the Z terminal to a key K; when this was pressed down, then, and only then, the other side of the B B′ condenser was connected with the battery, and it became charged. With the condenser in action strata were produced in V, and the tell-tale tube V^2 was illuminated, showing that an induced current was produced in the secondary wire; this we ascribed to a periodic overflow from the condenser, in addition to the current which was passing continuously from the battery.

230.—One of the most beautiful examples of the difference of discharge, with and without the condenser, was presented in December, 1874, by tube 53, which is represented in fig. 67, half-size. The negative wire lies in the axis of the tube, and reaches to within 0·25 inch of the positive terminal which enters the tube at right angles to it. On the negative wire are several glass beads or bugles, kept in place by expanding the wire in one direction by a slight blow with a hammer; the resistance of the tube, which was charged with carbonic acid, was found to be 50,000 ohms. With 980 powder cells, without the condenser, a beautiful tuft of violet light appeared on each of the spaces of uncovered wire, without the slightest indication of stratification, but on pressing down the key K in fig. 66, so as to connect the battery with a condenser of 0·5442 m.f. capacity, the tell-tale tube lighted up, and the discharge throughout tube 53 was stratified, as shown in fig. 67, the strata on the uncovered portions of the wire being violet, and those on the glass-covered part salmon coloured, and much fainter.

Fig. 67.

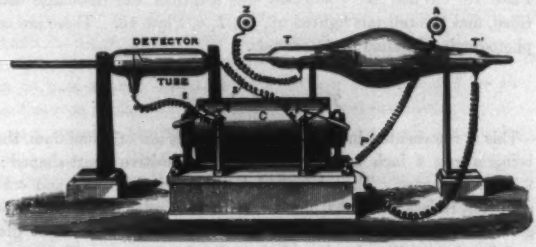


In order to produce these effects, we find that it is essential to use an induction coil, the primary of which presents very little resistance; for example, Apps's 815, the particulars of which are given in Part I., page 106, the resistance of the primary being only 0·245 ohm. They cannot be obtained by using the induction coil 819, Part I., page 64, this offering too much resistance, 316 ohms.

In order that the copies of the photographs in Plate 18, referring to the phenomena, may be understood, we insert fig. 68, which shows the disposition of the tube T T′,

the coil 815, and the tell-tale tube which is placed close to T T′, so that it may be photographed at the same time as T T′. The A terminal of the battery is connected to the primary of the coil at P′, the other end of the primary being connected through the wire P to the tube; the second wire of the tube is connected to the Z terminal of the battery; the ends of the secondary wire of the coil to the terminals of the tell-tale tube. The condenser is not shown in fig. 68.

Fig. 68.



In all the figures on Plate 18 relating to these phenomena, namely, figs. 6, *a* and *b*, 7, *a* and *b*, and fig. 8, *a* and *b*, the copy of the *a* photograph represents the condition of things when the condenser *is not* connected with the battery, the copy of the *b* photograph the phenomena when it *is* connected. In the *a* series there is no stratification in the vacuum tube and no illumination of the tell-tale tube, in the *b* series there is stratification, and the tell-tale tube is illuminated in consequence of an induced current, produced by the periodic overflow of the condenser and consequent pulsation of current, which coincides with the production of strata.

Tube 42, *Coal Gas.*

231.—Tube 42 is represented in fig. 37, its extreme length is 12·5 inches, between the terminals 2·125 inches, its greatest diameter 3 inches, the resistance 85,000 ohms. 1080 cells, C. 0·00912 W, without the condenser, produced a nebulous light around the cup-shaped negative and reaching the heart-shaped positive, but without any strata being visible in the discharge; the tell-tale tube was not illuminated, thus showing that there was no detectable pulsation in the current, fig. 6, *a*, Plate 18. When, however, the condenser was connected with the battery by pressing down the key K, fig. 66, then the discharge was a stratified one, and the tell-tale tube indicated by its illumination that the current through tube 42 was a pulsating one, fig. 6, *b*, Plate 18. These two figures are copied from photographs each taken in 60 seconds.

Tube 44.

232.—Similar in shape to 42, but with two magnesium spherical terminals 0·375 inch in diameter, distance between them 2·25 inches, the largest diameter of the tube 3·125 inches, resistance 42,000 ohms. With 1080 cells, without the condenser, C. 0·01331 W, a spherical nebulous glow around the negative ball, a slight glow on the positive, and no illumination of the tell-tale tube, fig. 7, *a*, Plate 18. When the condenser was attached the discharge became stratified, and the tell-tale lighted up, fig. 7, *b*, Plate 18. These are copied from photographs obtained in 60 seconds.

Tube 32, *Coal Gas.*

233.—This is represented in fig. 37; the terminals are of aluminium, the negative being a cup 1 inch in diameter, and the positive heart-shaped; they are 2·75 inches apart. The elongated bulb is 7 inches long and 4·5 inches in diameter, resistance 57,000 ohms. With 1080 cells, C. 0·01390 W, a nebulous glow on the negative without any stratification, and a slight glow on the positive, but no illumination of the tell-tale, fig. 8, *a*, Plate 18; with the condenser a stratified discharge and the tell-tale brilliantly illuminated, fig. 8, *b*. By charging up the condenser of 44·8 m.f. and allowing it to run down through the tube, it was ascertained, by measurement with the electrometer, that the current of 415 cells would just pass.

The battery of 1080 cells gave a current of ·03754 weber in short circuit; the condenser employed in all cases was $\frac{1}{6}$th of G, Part I., page 99, having a capacity of about 0·66 microfarads; when brought into action, by pressing down the key K, fig. 41, there was no intervening resistance between it and the battery, and supposing it to be completely discharged automatically as soon as it was charged to the full potential, the current was sufficient to effect this 52·77 times in a second.* To pass through the tube, however, the battery-current had to expend a certain amount of electro-motive force to overcome the impediments offered by the residual gas in the tube, and also the small resistance of the primary of the induction coil, so that the potential in the condenser might become somewhat higher than that necessary to overcome these impediments, and therefore from time to time an extra current from the condenser could pass through the tube, producing pulsations in the current through the primary of the induction coil, which are rendered evident by the glow in the tell-tale tube connected with the secondary wire of the coil. These

* The time required to charge the condenser to the potential of 1 volt would be $\frac{1}{0\cdot03754} \times 0\cdot00000066 = 0\cdot00001758$ second, or it would be charged to the potential of 1080 cells (assuming them to be equal to volts) $\frac{1080}{1\cdot0\cdot0} = 52\cdot77$ times per second.

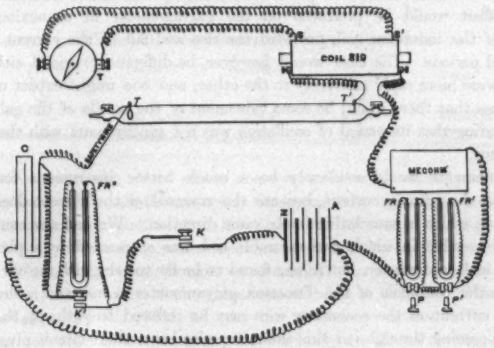
intermittent extra currents would in all probability occur when the potential of the condenser had risen only a very little above that of the terminals in the tube, and would consequently take place very many times more rapidly than 52·77 times in a second of time, as nothing approaching the full charge of the condenser passes on these occasions.

The phenomena do not occur when a very large condenser, 42·8 microfarad for example, is employed in the way shown in fig. 26, Part I., page 100, for then no current passes through the tube until the condenser has become charged to a sufficiently high potential, and this occupies a sensible time, about thirty seconds, and when it passes it does so continuously and steadily.

On the other hand with a small condenser, used as shown in fig. 66, the current commences to pass almost instantaneously through the tube, and in all probability divides itself as soon as the key K is pressed down, part continuing to pass through the tube, and part entering the condenser and discharging itself intermittently through the tube.

In order to test whether it would be possible to render evident pulsations, in the current, too feeble to cause the illumination of the tell-tale when perfectly steady strata are produced in tubes containing residual gases, we arranged the detector apparatus as shown in fig. 69.

Fig. 69.



A Z is the battery; A being connected through the fluid resistances FR FR′ (which can be plugged out of circuit by means of P and P′), the megohm, and the primary of coil No. 819, to the terminal T′ of the tube; A is also connected direct to one plate of the condenser C. Z is connected through the key K to the fluid resistance FR″ (which can be plugged out by pressing down the key K′), thence to

the other plate of the condenser, and through the safety wire to the other terminal T of the tube. The secondary wire of coil 819 is connected to a delicate THOMSON galvanometer T.

The apparatus being so arranged, if K is pressed down the condenser charges up (more rapidly when K′ is also pressed down than when the current is allowed to pass through the resistance FR″), and when it has reached a certain potential the current commences to pass steadily through the tube and the primary of the induction coil 819, and will continue to do so after the connexion with the battery is interrupted by raising the key K.

The condenser discharges itself more or less rapidly through the tube according to its resistance, and the external resistance introduced into the circuit at FR, FR′, and the megohm. The fluid resistance FR″ has no effect upon the time occupied by the charge running out of the condenser, as the current does not pass through it when the key K is allowed to rise so as to disconnect the battery, as will be easily seen by referring to the diagram. The only use of FR″ is to regulate the rate of *inflow* of the charge, and it may be so adjusted as to feed the condenser exactly as fast as it loses its charge. By pressing down the keys K′ and K the condenser is maintained at the highest potential possible with a given number of elements, a given tube, and a certain external resistance.

It is quite evident that even if pulsations do take place in the current through the tube, no effect would be produced on the galvanometer in connexion with the secondary of the induction coil, provided the rise and fall of the current were equal and in equal periods. The case would, however, be different provided either the rise or the fall were more rapid relatively to the other, and one might expect under these circumstances that there would be some movement of the needle of the galvanometer, notwithstanding that its period of oscillation was not synchronous with the pulsations of the current.

A dynamometer would evidently be a much better instrument for detecting pulsations in the primary current, because the reversal of the current does not affect its deflection, which is cumulative in the same direction. We had one constructed as delicate as possible in which the moveable coil was suspended by a platinum wire only 0·001 inch in diameter, but it was found to be far too sluggish for our purpose.

Between the terminals of the THOMSON galvanometer is inserted a shunt-box, by which the current of the secondary wire may be reduced to $\frac{1}{10}$th, $\frac{1}{100}$th, or $\frac{1}{1000}$th part before passing through it; this shunt-box also has a short-circuit plug, by means of which, when so desired, the current may be entirely shut off from the galvanometer. The shunt-box is not shown in the diagram.

In order to ascertain the direction of the current in the secondary wire, the condenser was disconnected in the first instance, the short-circuit plug of the galvanometer being removed, and contact made with the battery so as to send the current through the tube, the swing of the galvanometer indicated the direction,

say to the right, for the make-contact or *inverse* current; the contact was then broken and the swing, say to the left, was that for break-contact or *direct* current. It is almost needless to state that the primary current was suitably reduced by inserting resistances in the circuit, and that of the secondary by the use of suitable shunts to prevent injury to the THOMSON galvanometer.

Having thus ascertained the direction of swing for *direct* or *inverse* currents, the condenser was connected up, the short-circuit plug having been previously inserted between the terminals of the galvanometer so as to prevent any disturbance of it on making contact; as soon as the condenser had acquired a sufficiently high potential the short-circuit plug was removed. If the battery were left on there was frequently a slight *inverse* (make-contact) current indicated by the swing of the galvanometer. If the battery was now (after the insertion of the short-circuit plug) disconnected, there was a continuous *direct* current observed as the charge of the condenser ran gradually down so soon as the short-circuit plug was removed. The first of the two cases was equivalent to an infinite number of make-contacts, the second to an infinite number of break-contacts. Many observations were made with coil No. 819, which we had taken to pieces several times during the course of our trials on account of suspected leakage from the primary to the secondary wire. It was ultimately entirely remade in February, 1878, and the secondary wire coiled on a separate ebonite cylinder to ensure efficient insulation, which was accomplished.

COIL 819 when altered was thus composed.

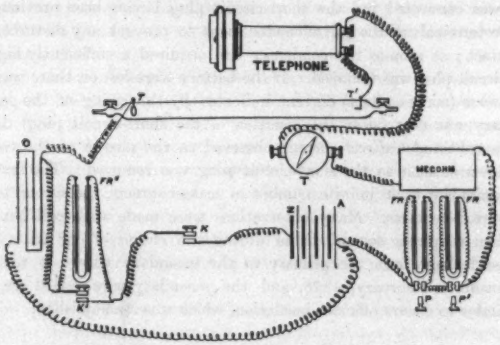
Approximate internal diameter.	External diameter.	Length of wire.	Diameter of wire.	Resistance.	Turns.
inch.	inch.		inch.	ohms.	
0·6	2·2	1700 yards	0·014	0·304	12920 primary.
3·2	4·6	14 miles	0·0033	42000	26289 secondary.

In every case where the strata are to the eye or rotating mirror perfectly steady, slight deflections of the needle are seen; these generally indicate a resultant *direct* current (break-contact), and in the fewer number of cases an *inverse* current indicating, in the first case, a *sudden* decrease and *slow* increase of current through the tube. These deflections, though very manifest, do not amount to more than about three or four divisions of the galvanometer scale, a deflection which indicates a current of only 0·00000000023 W. At the advent or retreat of a stratum at the positive pole there is frequently produced a deviation of 300 divisions, indicating a current of 0·00000001812 W; before a stratum leaves the positive terminal or dies out on it, there is usually a tremulous motion of that stratum visible to the eye and indicated by rapid pulsations of the galvanometer.

On the suggestion of Professor CLERK MAXWELL we have recently introduced the telephone into the primary current, as shown in fig. 70, and also in the secondary current of coil 819.

In all cases where the condenser C was discharging itself gradually through the tube a low rustling sound was distinctly audible to sensitive ears so long as the stratification remained *apparently* perfectly steady. When the phase of confused stratification, which immediately precedes extinction, was reached, the sound in the

Fig. 70.



telephone became very loud and rose in pitch, with some tubes becoming quite shrill. These results, therefore, confirm the conclusion already arrived at from other experiments, namely, that the discharge in vacuum tubes is intermittent; but we do not pretend that they make it manifest that stratification is *dependent* upon intermittence.*

In the course of our experiments we have arrived at the following facts :—

1. *The discharge in a vacuum tube does not differ essentially from that in air and other gases at ordinary atmospheric pressures; it cannot be considered as a current in the ordinary acceptation of the term, but must be of the nature of a disruptive discharge, the molecules of the gas acting as carriers of electrification.*

* Mr. Spottiswoode informs us (June 3, 1878) that he has also tried the telephone inserted in the circuit, both from the Holtz machine and from the great condenser, and found that the rushing noise was coincident with well developed striæ. The sound, however, occasionally became inaudible (to human ears, D. and M.), and afterwards recovered its strength. When the tension in the condenser fell below a certain point, or the speed of the machine was reduced below a certain rate, indicated by a sudden change in the configuration of the striæ, the rushing noise was replaced by a musical note, the pitch of which fell with the tension. The range of this note was in some cases considerably greater than an octave, and its pitch fell more often by semitones than gradually. The range both in pitch and in duration was increased by resistance introduced in the circuit. The pitch of the note was lowered by bringing the finger near to the tube, and thereby constricting the discharge.

The gases in all probability receive impulses in two directions at right angles to each other, that from the negative being the more continuous of the two. Metal is frequently carried from the terminals and is deposited on the inside of the tube, so as to leave a permanent record of the spaces between the strata.*

2. *As the exhaustion proceeds the potential necessary to cause a current to pass diminishes up to a certain point, whence it again increases, and the strata thicken and diminish in number, until a point is reached at which, notwithstanding the high electromotive force available, no discharge through the residual gas can be detected.*† Thus, when one pole of a battery of 8040 cells, was led to one of the terminals of tube 143, fig. 37, which has a radiometer attached to it, the other terminal of the tube, distant only 0·1 inch, being connected through a sensitive THOMSON galvanometer to the other pole of the battery (earth), the current observed was not greater than that which was found to be due to conduction over and through the glass. Although no current passed, the leading wires acting inductively stopped the motion of the radiometer, as has been observed by Mr. Justice GROVE.

3. *All strata have their origin at the positive pole.* Thus, in a given tube, with a certain gas, there is produced at a certain pressure, in the first instance, only one luminosity which forms on the positive terminal, then, as the exhaustion is gradually carried further it detaches itself, moving towards the negative, and being followed by other luminosities, which gradually increase in number up to a certain point.

4. *With the same potential the phenomena vary irregularly with the amount of current.* Sometimes, as the current is increased, the number of strata in certain tubes increases, and as it is diminished their number decreases; but with other tubes the number of strata frequently increases with a diminution of current. If the source of the current is a charged condenser, the flow being from one of its plates through resistances and the tube to the other: then, as the potential of the condenser falls and the current diminishes, the number of strata alters; if the strata diminish in number with the fall of potential, then the stratum nearest the positive wire disappears on it, the next then follows and disappears, and so on with others; if, on the other hand, the charge of the condenser is very gradually increased, the strata pour in, one after the other, in the most steady and beautiful manner from the positive.

5. *A change of current frequently produces an entire change in the colour of the strata.* For example, in a hydrogen tube from a cobalt blue to a pink.

* DE LA RUE and MÜLLER, Phil. Trans., 1878, Vol. 169, p. 90 and p. 118.

† From observations with pressure varying from 6·4 to 145·1 millims., WIEDEMANN and RUHLMANN conclude that the accumulation requisite to produce discharge increases with the pressure at first quickly, then more slowly; towards the upper limit of their experiments it becomes nearly proportional to the pressures.

It also changes the spectrum of the strata; moreover, the spectra of the illuminated terminals and the strata differ.

6. *If the discharge is irregular and the strata indistinct, an alteration of the amount of current makes the strata distinct and steady.* Most frequently a point of steadiness is produced by the careful introduction of external resistance; subsequently the introduction of more resistance produces a new phase of unsteadiness, and still more resistance another phase of steady and distinct stratification.

7. *The greatest heat is in the vicinity of the strata.* This can be best observed when the tube contains either only one stratum, or a small number separated by a broad interval. There is reason to believe that even in the dark discharge there may be strata; for we have found a development of heat in the middle of a tube, in which there was no illumination except on the terminals.

8. *Even when the strata are to all appearance perfectly steady, a pulsation can be detected in the current; but it is not proved that the strata depend upon intermittence.*

9. *There is no current from a battery through a tube divided by a glass division into two chambers, and the tube can only be illuminated by alternating charges.*

10. *In the same tube and with the same gas, a very great variety of phenomena can be produced by varying the pressure and the current. The luminosities and strata, in their various forms, can be reproduced in the same tube, or in others having similar dimensions.*

11. *At the same pressure and with the same current, the diameter of the tube affects the character and closeness of the stratification.*

Our special thanks are due to Professor Stokes for many valuable suggestions and criticisms during the course of our investigation.

We have very great pleasure in stating that during the last twelve months we have had the benefit of the zealous assistance of Mr. W. Sharpey Seaton, formerly in the service of Professors Sir Wm. Thomson and Fleeming Jenkin, and that we have found his familiarity with electrical measurements, and his resources in devising methods of overcoming the many impediments we have encountered in connexion with them, of the greatest value. Mr. Fram has continued to give us zealous, intelligent, and patient assistance, and has helped us over many difficulties. The photographs copied in Plates 15–18 were taken by Mr. H. Reynolds, Mr. De La Rue's former assistant in astronomical photography.*

Our experiments are still going on, and we may have, at a future time, some more

* Phil. Trans. 1862, pp. 333–416.

facts to contribute to the general stock of knowledge; but the field before us is so inexhaustible, that we think it better to offer the small amount of produce we have collected, with much labour, rather than wait, and by slightly increasing the offering, make it more acceptable. We are now engaged in determining the differences of potential between the terminals corresponding to different pressures with a given gas and a given vacuum tube. We defer for the present the suggestion of any theory to account for stratification, in the hope of being able to confirm experimentally certain views which we entertain as to the cause of this phenomenon.

April 10*th*, 1878.

ERRATUM.

Part I., page 112, *for* $\frac{0{\cdot}0001713 \times 63{\cdot}4}{10} =$

read $\frac{0{\cdot}0001713 \times 63{\cdot}24}{10} =$

APPENDIX.

Note A, relating to Page 155.

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NOTE B, RELATING TO PAGE 168.

GROVE (Phil. Trans., 1852, p. 87) makes the following conjecture on this subject in his paper on the Electro-Chemical Polarity of Gases: "Whether gases at all conduct electricity, properly speaking, or whether the transmission is not always by the disruptive discharge, the discharge by convection, or something clearly analogous, is perhaps a doubtful question; but I feel strongly convinced that gases do not conduct in any similar manner to metals or electrolyte."

BECQUEREL made a most elaborate series of experiments on the "conductivity" of gases at high temperatures—red heat, and beyond. These are described very fully in the Annales de Chimie, xxxix., 1853, pp. 355–402, and in abstract in the Comptes Rendus, xxvii., 1853, pp. 20–24. The discharge was obtained between two concentric cylinders, namely, a strained wire in the axis of a tube, both being of platinum; the tube was capable of being closed at the ends so as to permit experiments at any pressure down to about 3 or 4 millims., the limit of his pump. He found that by heating the tube to incandescence he could produce a discharge with one cell even at atmospheric pressure, and that the current was still further increased if the pressure were diminished. This result applied to all gases, pressures and temperatures tried, commencing at incandescence. The order of "conductivity" at a red heat at atmospheric pressures with one cell was, hydrogen, oxygen, chlorine, $\left\{\begin{matrix}\text{air,}\\\text{nitrogen,}\end{matrix}\right\}$ carbonic anhydride; but with very high temperatures and small pressures there seemed to be a tendency to equal "conductivity."

He introduced a "rheostat," consisting of a U tube filled with fluid into which wires could be inserted to a less or greater depth, and having adjusted the resistance so as to obtain a given deflection when the tube was in circuit, he subsequently put the tube out of circuit and again adjusted the rheostat so as to obtain the same deflection; the difference between the two readings was taken by him as the resistance of the tube in terms of the rheostat.

Although he interprets his results differently, and is inclined to consider that gases at high temperatures really *conduct* electricity, they seem to us to support our hypothesis that the discharge is a disruptive one in all cases, even at the high temperatures he experimented with. For his measurements show that when he employed a definite potential and adjusted the external resistance to produce different currents, the resistance of the gas appeared to decrease with the increase of current, this agreeing so far with our results. But we are quite at a loss how to reconcile the following experiments with ours:—

"La seconde série de déterminations experimentales met en évidence un fait assez curieux: c'est que pour la même intensité électrique (the same amount of current), la resistance de l'air chauffé au rouge est d'autant plus grande que le nombre des éléments de la pile est aussi plus grand." Being unable to render an account to ourselves of this very remarkable result, we have, May 28th, 1878, made some experiments with tube 31, employing 1200, 2400, 3600, 4800, and 6300 cells, and by the introduction of wire resistance maintained a constant deviation of the galvanometer of 29°, we found that the *apparent* resistance of the tube was represented in each case by about 30,000 ohms. Our experiment differed from that of Becquerel, in that we employed rarefied gas at ordinary temperature instead of heated gas at atmospheric pressure, and our rheostat consisted of wire and not of a liquid electrolyte.

Wiedemann and Rühlmann (Poggend. Ann., cxlv., pp. 235-259, 364-399) by very different means have apparently arrived at the same result as our own. They started from the ground that the observations of one of them (G. Wiedemann) on the amount of heat generated in a Geissler-tube had demonstrated that rarefied gases did not behave like metallic conductors as had been asserted by other experimentalists (Morren, Ann. de Chim. et de Phys., 4e série, iv., p. 325; Poggend. Ann., cxxx., p. 612; De la Rive, Compt. Rend., vi., p. 669: Archives de Genève, nouv. sér., xvii., p. 53; Hittorf, Pogg. Ann., cxxxvi., p. 201, &c.); for the heat generated in the tube was far from varying as the *square* of the current. Wiedemann and Rühlmann selected for their source of electrification the Holtz machine, which was driven by a hydromotor, so as to give a constant current, and had so great an internal resistance as to render negligible the resistance of the external part of their circuit. By ingenious contrivances they succeeded in measuring the time-interval between the rapidly-succeeding flashes of which the discharge in rarefied gases, under the circumstances of their experiments, was proved to consist. They found that, when other things were kept constant and the current alone varied, the time-interval between a pair of successive discharges was inversely proportional to the current: in other words, the quantity which flowed across the tube at each discharge was constant for all the values of current investigated by them. Hence, as fast as a certain definite accumulation of electricity (density) was attained on the terminals, these discharged themselves, became recharged to the same accumulation and discharged themselves again, and so on. So far, therefore, as their observations extend, they seem entirely accordant with our own result stated above, for it is obvious that as the interval between the discharges in their experiments did not exceed 0·002 second, the effect on any electrometer as yet devised would be practically the same as if the terminals were kept constantly charged to that potential which they have when the accumulation is sufficient to cause discharge; *à fortiori*, would this be the case when a battery of small internal resistance is substituted for the Holtz machine. The range of Wiedemann and Rühlmann's observations on this point appears, however, to have been very limited; in their illustrations of the constancy of the quantity flowing across at each discharge when the current is varied, the relation between the maximum and minimum currents employed is 40 : 24·5.

Note C, relating to Page 221.

In support of the observation as to possible dependence of stratification upon the concurrence of axial and radial impulses from the positive and negative terminals respectively, we quote the following experiments :—

Gassiot (Phil. Trans., pp. 1–16) used tubes supported in a vertical position, in which were produced Torricellian vacua, with an arrangement for causing the mercurial column to rise and cover one terminal or fall, and leave it exposed. "When the upper wire is negative and the lower positive, if the mercury in the globe is allowed to ascend the tube, the stratifications collapse, but the dark band between them and the negative glow remains; as the mercury rises the stratification merges into a series of rings on the surface of the mercury, which when the circuit of the primary is broken is not found to be tarnished, but as bright as when the experiment commenced. On reversing the direction of the current, when the mercury is permitted to ascend immediately it covers the negative wire the stratifications disappear and the interior of the globe is filled with bluish light; a bright spot of light is visible on the end of the positive wire, but the mercury no longer exhibits the red glow, its entire surface, until it ascends to within an inch of the positive wire, being covered with a brilliant white phosphorescent film about one-eighth of an inch in thickness."

He also (Phil. Trans., 1859, pp. 137–160) had constructed a tube in which a moveable terminal might be made to drop into a brass tubular case surrounded by a glass protecting tube of small bore which projected beyond the brass case, so that the point could at will be made to project beyond this glass sheath or to fall within it. "When both wires were exposed the stratified discharges show the clear cloud-like appearances so often described, whether A (the moveable terminal) is positive or negative; but if A is made negative and the tube inclined so as to let the wire drop into the brass tubing, almost all trace of stratifications immediately disappear."

He found that if he enclosed the terminals in a glass tube of very small bore projecting about an eighth of an inch beyond the end of the wire, the emanation from the negative might be constrained to take a forward direction. "The negative discharge issuing through the orifice as from a jet. . . . . If the wire (negative) is inclined a little the discharge will impinge against the side of the vacuum tube, brilliantly illuminating the spot on which it impinges. . . . . If the discharge is continued for a few seconds that portion of the tube on which the discharge impinges will be sensibly heated."

Gassiot also states (Phil. Trans., 1858, p. 10) that: "The emanation of particles only proceeds from the negative, not in a direct line from the positive, but laterally." Again, p. 11: "Such particles being always deposited in a lateral direction from the wire, and not beyond the line on the glass tube even with the end of the wire." p. 13: "The force from the positive is not accompanied by the transfer of particles from the metallic terminal."

Hittorf (Pogg. Ann. cxxxvi., 1869, pp. 1–31 and 137–194) describes various experiments bearing on this point. Thus, in a tube having two parallel electrodes at 4 m.m. distance, the negative glow radiated in all directions through the tube, but the positive discharge appeared only on the side of its terminal which was remote from the negative electrode. In another tube it was observed that when one of the terminals was bent back upon itself, if this is made positive, the discharge curls round so as to present itself towards the negative; but when the bent terminal is made negative the glow remains directed away from the positive. He also describes an interesting experiment which exhibits in a striking manner the influence of the size of the space surrounding the electrodes, but it is complicated by the influence of the distance between the terminals, which latter influence has a value varying with the degree of rarefaction as shown by other experiments of the same physicist (*see* footnote, p. 163). A vessel consisting of two spherical glass bulbs joined by a short glass tube of 1 m.m. in diameter had two straight wires, for terminals, running horizontally one through each bulb and extending into the junction-tube so as to leave a space of only 1 m.m. between their extremities. The bulbs were also connected at the upper ends of their vertical axis by another long glass tube of the same bore as the

short junction-tube. As the gas within the double vessel was rarefied, the discharge which, at higher pressures, had passed exclusively through the short tube began to divide itself and passed through the long circuitous route in proportion increasing with the decrease of pressure until a degree of rarefaction was attained, at which it passed *exclusively* through the long junction tube.

It has been noticed by ourselves and others that the size of the negative terminal has considerable influence upon the general character of the discharge, and that with a very small negative it is difficult to produce striæ at all.

With a view of testing this further, SPOTTISWOODE constructed a tube in which the length of one terminal could be altered, while the total distance between the extremities of the two terminals remained unchanged. With this contrivance it was found that when the negative terminal was lengthened the dark space was shortened by a prolongation of the positive column. Thus the tube being about 12 inches in length, an increase in the length of the negative terminal from 3 to 6 inches caused a diminution in that of the dark space from 3 to 1·5 inches.

The importance of size of the negative terminal was also illustrated by SPOTTISWOODE in a striking manner with a tube 18 inches in length and 1·75 in diameter, containing from 30 to 50 cubic centimetres of mercury. When the tube was laid on its side so as to leave the negative terminal, which was small, free from mercury, the tube was filled with an unbroken glow of light; but as soon as the mercury touched the terminal, a fine column of striæ was developed. When the mercury spread along any considerable part of the tube, the column still stretched out towards the negative terminal; but it was repelled to the side of the tube opposite to that occupied by the mercury, and the individual striæ assumed an oblique position, as if under the influence of two forces, one along the other at right angles to the axis of the tube.

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IX. The Bakerian Lecture.—*On Repulsion resulting from Radiation.*—Part V.

By William Crookes, *F.R.S., V.P.C.S., &c.*

Received December 3, 1877,—Read January 17, 1878.

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INTRODUCTION.

220. In this Part I propose to give the results of some researches which, during the past twelve months, have occupied much of my time. The researches include a quantitative examination of the repulsion exerted by a standard flame shining on pith and mica disks, coated with various powders, chemical precipitates, &c., and suspended *in vacuo* in a torsion apparatus. The character of the incident radiation has been varied by straining it through water, alum, or coloured media; the action of good and bad conductors of heat has been compared; and the influence which favourable presentation of the experimental surface, by curvature or obliquity, has upon its movement has been investigated, with the result of throwing much light on some of the debated problems in molecular physics to which, by general assent, the repulsion resulting from radiation is held to be due. In every step of this investigation, theory and observation have gone hand in hand, and at each point gained it has been my endeavour to permanently record such experimental proof in the convenient form of an instrument, so as to have it available for further examination.

The reaction, along lines of greatest molecular pressure, between the experimental surface and the fixed case containing it, has been examined. Experimental proof has been obtained, not only of the existence of such a reaction, but of the direction in which it is chiefly exerted; and the apparatus devised during this inquiry, to put each step of the theory to an experimental test, has led to the construction of a modification of the radiometer named the *otheoscope*, in which the reacting surface is no longer the side of the glass case, but is specially made with a view of getting the greatest sensitiveness in the moving parts of the apparatus. Owing to the increased delicacy of the instruments now made, it has been possible to detect the existence of molecular pressure when radiation falls on a black surface, in air of normal density.

MULTIPLE DISK TORSION APPARATUS.

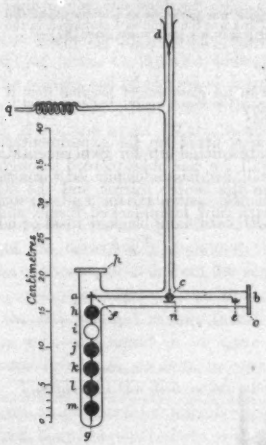
221. The apparatus used to get quantitative measurements of the repulsion produced by radiation on disks of various kinds, and coated with different substances, is similar in principle to the one described in Part IV. of these researches* (198, 208); but as it differs in many important details of construction it is here fully described. The torsion apparatus is represented in elevation in fig. 1.

a b is a horizontal glass tube containing the beam, which in this case is made of straw, so as to secure lightness with absence of flexure under the comparatively heavy weights it sometimes has to bear; glass was used at first, but it was found to bend too much. *c d* is a fine torsion fibre of glass (103), to which the beam is suspended;

* Phil. Trans., 1876, pt. 2, p. 365.

it is cemented at d to a well-ground stopper, so as to admit of adjustment. When in position, cement (83) is run round the stopper. At c, the point of junction between the torsion fibre and the straw beam, is a silvered glass mirror. At the end, e, of the beam is a small pan to hold the weights counterpoising the disks which are suspended to the other end. A flat stirrup of aluminium, at f, fits stiffly on the straw beam, and

Fig. 1.



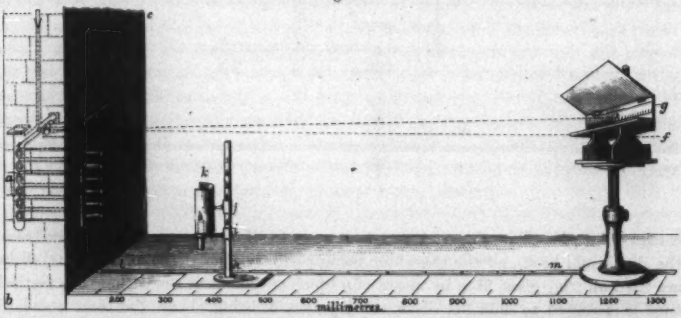
carries a flat glass fibre, $f\,g$, cemented to it so as to allow of no play; the straw beam, the aluminium hook, and the glass fibre being perfectly rigid. The experimental disks are fixed on the glass fibre by means of a touch of cement at the back. The vertical tube is arranged to hold six disks, the top one, h, being always the same standard lampblacked pith; the others, i, j, k, l, and m, being changed each time. A small magnet, n, attached to the central mirror, and controlled by a bar magnet outside, gives the power of bringing the beam to zero, should it happen to get out of adjustment, without having to melt the cement and alter the angle of the torsion fibre by turning the stopper d. Plate glass caps at o and p, cemented to the ground edges of the tubes, give access to the interior; o allows the counterpoises to be adjusted in the pan, and p allows the aluminium stirrup to be unhooked and the whole of the disks to be lifted out together. The apparatus is connected to the mercury pump by the arm and spiral q.

The weights and dimensions of the various parts of the apparatus are as follows:—

Weight of straw beam, mirror, magnetic needle, aluminium stirrup, and flat glass fibre, &c.	7·25 grains.
Average weight of six plain mica disks	2·40 „
Average weight of six plain pith disks	0·59 „
Length of straw beam, from centre of counterpoising pan to centre of disks	17·0 centimetres.
Length of arm, from centre of suspension to centre of pan	7·6 „
Length of arm, from centre of suspension to centre of disks	9·4 „
Glass torsion fibre (this was the same as I employed in the experiments described in my last paper, par. 199)—	
Length	23·0 „
Thickness	0·0013 inch.
Torsion, with the glass weight hanging from it (186, 199)	½ oscillation in 15·75 seconds.

Fig. 2 shows the apparatus fitted up for experimentation. The disks are shown in position at *a*; a brick wall, *b c*, has holes pierced through it in two places, as shown, one hole, *d*, being opposite the centre mirror, and the other, *e*, opposite the disks. The aperture *d* is lined with card, lampblacked inside, and the interstices between it

Fig. 2.



and the bricks are well plugged with cotton wool. A water cell at *d* prevents radiant heat from the lamp getting to the apparatus. Through the hole *e* pass six card tubes, lampblacked internally, 20 millims. diameter and 23 centims. long. The tubes are firmly cemented to the wall, so that each shall be exactly central with its corresponding disk, and the outer end of each is closed with a cork. The space between the tubes and wall is well stuffed with cotton wool. The apparatus, being once fixed in position, is surrounded on all sides, as well as above and below, with cotton wool. Outside this is a row of glass bottles filled with water, and in front of all is a wooden screen. When protected in this manner, the inside of the apparatus is found to be free from

disturbances caused by change of temperature. When the disks have to be changed, air having been let in through the pump, access is easily obtained to the glass cap *p* (fig. 1), and the cement being softened by heat, and the cap removed, the disks are lifted out together by seizing the aluminium stirrup with forceps. A fresh set of disks being introduced, the apparatus is again packed up, and re-exhausted.

A lamp at *f* throws a narrow beam of light on the mirror of the apparatus, through the aperture *d*. The ray is reflected to the scale *g*, where its deflection from zero shows the angular movement of the torsion beam when one of the disks is repelled by radiation. The scale is $1\frac{1}{2}$ metre from the reflecting mirror.

A standard candle (109) is supported on a heavy stand, *h*, and can be raised or lowered by means of the sliding piece, *i*. Another sliding piece, *j*, carries a pointed wire projecting from it. The upright rod of the stand is graduated and numbered, so that when the sliding piece *j* is at mark 1, the point of the wire is on the prolongation of the axis of tube and disk No. 1, and so on. Then by sliding the candle up till the most luminous part of the flame is level with the point of the wire, it is known that the light will shine full on the disk under experiment. A half cylinder, *k*, covered with black velvet, protects the candle from draughts. The candle stand, *h*, slides along a straight edge, *l m*, screwed to the bench, so graduated that by bringing a mark on the sliding stand to one of the divisions, it indicates the number of millimetres separating the surface of the experimental disk from the centre of the candle flame.

222. The experimental powders are laid on one surface of mica or pith disks, 17·6 millims. in diameter, the pith being 1 millim. thick. If unaffected by alcohol, the powders are ground up with this liquid in an agate mortar, and then laid on somewhat thickly with a camel-hair brush, so as to be certain that the whole surface of the disk is well covered. The back of the disk is left plain. If affected by alcohol, water is used; but in any case no gum or other adhesive agent is added. When disks of mica or thin metal are used, they are punched out with the same tool employed for the pith, and care is taken to completely flatten the disk and to remove the burr. Where the material for the disks cannot be punched (*e. g.* charcoal, selenium, rock salt, &c.) they are cut or filed to shape. The upper disk, *h*, in the apparatus is never removed; it consists of a pith disk, coated with lampblack, by painting with a thin cream of lampblack and alcohol, and after drying smoked over burning camphor (147). The other disks are attached to the flat glass fibre, *f g* (fig. 1), by a minute piece of cement at their backs, and the whole series is lowered into its place, as shown in fig. 2, and fixed in a vertical position. The cap *p* is then cemented on, and the air is rarefied by means of the pump to within one millimetre of a vacuum. It is kept at this exhaustion for about twelve hours, when the disks and powders become perfectly dry under the influence of the phosphoric anhydride which is in the drying tube of the pump (26, 51, 82, 355).* The lamp and scale are now adjusted, and the luminous index brought to zero, if necessary, by moving the control magnet.

* Proc. Roy. Soc., Nov. 16, 1876, No. 175, p. 306.

The standard candle being lighted and placed 500 millims. from No. 1 disk (standard lampblack), exhaustion by the pump is carried on till such a point of sensitiveness is reached that on removing the screen the standard disk is repelled so that the luminous index moves about 150 divisions on the scale. Under ordinary circumstances the standard candle is kept 500 millims. from the disk, but, when its force is enfeebled by interposed screens, the distance is diminished so as to increase the amplitude of swing of the luminous index.

223. It is necessary to carefully exclude aqueous vapour from the interior of the torsion apparatus, otherwise the sensitiveness will be diminished (105, 130). In all the series of experiments with different disks, the exhaustion, too, must be as nearly as possible uniform, otherwise the proportion between the standard disk and the others will not be identical. With a very good vacuum, when the apparatus is most sensitive, the amount of movement impressed on the experimental disks diminishes in greater proportion than that shown by the black disk; in other words, as the vacuum becomes very good, the sensitiveness of the black surface increases at a greater rate than does that of most of the other surfaces. In illustration I may take an experiment in which a pith disk coated with precipitated oxide of zinc was compared with the standard black disk. The candle being 900 millims. from the disks, the experiment was tried as soon as the exhaustion was good enough to cause a fair movement of the index ray. The ratio between the black and the white disk was as 100 to 55·5. On continuing the exhaustion for some time and then repeating the experiment, the ratio between the black and the white became as 100 to 42·5, and when the exhaustion was at the usual height at which the experiments were tried the ratio was as 100 to 35. In all cases, the actual amount of repulsion on the disks was greater at the higher than at the lower exhaustions. When sufficient air is present in the apparatus to visibly depress the gauge, the repulsion on the black and white surfaces tends to get still more nearly equal. These results are curiously analogous to those described in my third paper on this subject,* pars. 128, 155, 170, 171, where it is shown that the less refrangible rays of the spectrum cause black and white surfaces to be repelled to almost the same extent; the ratio between the black and the white increasing as the incident rays increase in refrangibility. In these instances, therefore, low refrangibility and low exhaustion produce similar results. The experiment described in par. 130 proves that at a high exhaustion the presence of residual aqueous vapour has the same effect in equalising the repulsive force of luminous radiation on black and white surfaces as is produced in dry air at a somewhat lower degree of exhaustion.

224. In the following Tables will be found the mean results of experiments with various powders laid on the surface of mica or pith disks.† The deflection of the

* Phil. Trans., Vol. 166, pt. 2, January 5, 1876.

† The action was about 50 per cent. stronger with mica disks than with pith disks (see Table XII., par. 237). But when reduced to the usual standard of lampblack=100, the differences ceased to be greater than might be due to experimental errors.

index ray of light was observed at intervals varying from a few hours to many weeks, several times with each powder, and the means were reduced to the standard deflection of the lampblacked disk = 100. The column headed "water screen interposed" is also reduced to the deflection of lampblack = 100. In comparing the two columns, it must be remembered that the actual amount of repulsion on the standard lampblacked disk when the water screen is interposed is only $\frac{1}{12}$th of the amount obtained when no screen is in the way, the distance of candle and other things being equal. In order, therefore, to compare one column with another the results in the column headed "water screen interposed" must be divided by 12.

TABLE I.—Black Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Iron reduced by hydrogen	101·1	107·2
Tungsten reduced by hydrogen	96·5	95·4
Palladium iodide	87·3	..*
Mercury sulphide	84·0	94·6

225. TABLE II.—White Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Hydrated zinc oxide	40·5	14·0
Barium sulphate	37·4	4·2
Magnesia, ignited	37·2	8·4
Oxamide	36·0	10·7
Silica, precipitated	33·6	4·1
Lead carbonate (white lead)	32·5	9·8
Mercury sulphethylate	28·5	15·1
Calcium carbonate	28·5	3·9
Lead sulphate	27·6	4·7

The powerful absorption for the invisible heat rays which these white powders exercise is somewhat remarkable. Assuming that the ultra-red rays from a candle are almost entirely cut off by a water screen, the comparatively strong action shown in the first column must be mainly due to absorption of the invisible rays of heat, and when these are filtered off through water the action is diminished 48 times.† A similar examination of Table I. shows that a water screen only diminishes the action about 11 times.

In paragraph 201 of a former paper on this subject I gave the result of an

* When dots occur in a column, they mean that no experiment was tried.

† Omitting lampblack, the average of the first column is 33·5, and that of the second 8·3. But, as already stated, the action behind water must be divided by 12, which reduces it to 0·7, about $\frac{1}{48}$th part of 33·5.

experiment with lead carbonate tried in a somewhat similar way. The effect was then found to be only 13 as against lampblacked pith=100. The much stronger effect now obtained (32·5) is probably due to the different physical condition of the two samples of lead carbonate. The one giving the lower number, was prepared in the wet way by double decomposition, whilst the sample now used was prepared in the dry way by the corrosion of metallic lead by carbonic acid and air in the presence of moisture and acetic acid vapour, as in the manufacture of white lead. It is well known that lead carbonate thus prepared possesses great density and opacity.

226. TABLE III.—Red Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Amorphous phosphorus	40·4	38·0
Precipitated selenium	35·8	69·5
Ferric oxide	29·5	25·1
Mercury and copper iodide	22·4	11·7

The results given in this Table deserve notice. The very high action shown by precipitated selenium in the second column (water screen interposed) is one which, considered alone, might be supposed to belong to its elementary character, and this view would in some measure be borne out by the similar behaviour of reduced iron in Table I.; but other elementary bodies—*e.g.*, phosphorus in Table III. and tungsten in Table I.—do not act in this way. The averages of columns 1 and 2 are 33·1 with no screen interposed and 36·1 with a water screen; if selenium be left out as anomalous, the averages become 32·2 and 24·9. In subsequent Tables (242) other bodies will be seen to act like selenium, although not to the same extent.

227. TABLE IV.—Brown Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Thallic oxide	121·7	111·0
Lead peroxide	113·5	105·0
Platinum protochloride	77·8	84·0
Copper ferrocyanide	71·2	87·8
Thallium vanadate	50·4	69·2
Bismuth peroxide	21·5	10·2

The very high action exhibited by the thallium and lead peroxides is worthy of notice. Of all the substances I have yet examined these head the list, thallium peroxide being more repelled under the influence of radiation than any other body. The averages of the columns, *without* and *with* a water screen, are 92·7 and 94·5.

Brown powders therefore act most like black. The low action of bismuth peroxide is probably due to its pale brown colour, which acts therefore like a mixture of brown and white. It will be understood that in classifying all varieties of coloured bodies under a few headings, great differences in intensity and tint must be associated together in the same Table.

228. TABLE V.—Yellow Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Tungstic acid (hydrated)	57·9	26·9
Tungstic acid (anhydrous)	50·8	72·2
Persulpho-cyanogen	43·9	11·5
Ceroso-ceric oxide	38·7	14·1
Uranic oxide	33·8	11·8
Cadmium sulphide	32·6	10·6
Milk of sulphur	30·5	7·7
Sulphur, precipitated	25·6	19·8
Antimonic acid	22·6	8·1

The averages of the two columns are, without a water screen, 37·4, and with a water screen, 20·3. But anhydrous tungstic acid behind water is so different from the others that a fairer mean will be obtained by omitting this powder. The figures now become 35·7 and 13·8.

229. TABLE VI.—Green Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Green salt of Magnus (diammonio-platinous chloride)	89·5	103·5
Chromic oxide, pale green	71·5	20·2
„ bright green	63·4	45·8

These are too few in number to make it safe to draw any inference from the results. The great difference in action behind a water screen caused by a little change in colour of chromic oxide is worth notice, and will be again referred to.

230. TABLE VII.—Blue Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Tungstic oxide	91·3	100·1
Copper carbonate	54·4	56·5
„ phosphate	52·0	52·1
„ tungstate	51·2	77·0
„ oxalate	30·1	40·2

These actions are of interest as showing a much stronger proportionate action behind a water screen than with no screen. The average of the first column with no screen is 55·8, whilst that of the water screen column is 65·2. At the conclusion of this tabulation of results I shall collect together the variations in the actions and comment upon them. The strong action on the oxide of tungsten is probably caused by its dark colour, the blue appearing almost black.

231. TABLE VIII.—Dyes and Colouring Matters of Organic Origin.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Bismark brown	52·7	42·6
Fluorescin	52·2	29·0
Magdala rose	47·0	32·5
Eosen	43·6	27·7
Saffranin	41·0	52·5
Product of the decomposition by acids of the green colouring matter of leaves (from Professor Stokes)	39·2	47·1
Aniline scarlet	37·0	21·7
Isatin	34·5	15·3

These organic substances do not show many striking variations. The saffranin, and the product of the decomposition of chlorophyll show an increased ratio of action when the heat rays are cut off by water. From the appearance of the spectrum of the chlorophyll product, Professor STOKES, who kindly prepared me the specimen, was led to believe that it would be little affected by invisible heat rays, but affected to a considerable extent by light. The figures in the two columns show that this theoretical reasoning is quite borne out by facts. The results obtained with the other organic colouring matters show that when the invisible heat rays are cut off, the action declines in proportion to that on the lampblack.

Leaving out saffranin and the chlorophyll product, the mean actions of the other substances are with no screen, 44·5; with a water screen interposed, 28·1. The results obtained for Bismark brown and aniline scarlet, behind a water screen, are not very satisfactory, and must only be considered approximations to the truth. It was difficult to get a definite position of rest for the luminous index, as after a certain time the oscillations increased in amplitude as the light continued to shine on the disk.

232. TABLE IX.—Metals.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Precipitated silver (on a pith disk)	57·8	58·3
Iron foil	48·4	5·1
Aluminium leaf (backed with mica)	28·7	45·0
Platinum leaf (backed with mica)	28·7	41·1
Platinum leaf	20·1	22·3
Lampblacked platinum leaf (black side exposed)	19·9	..
Gold leaf	19·3	51·0
Lampblacked silver leaf (black side exposed)	17·7	..
Aluminium leaf	13·8	13·6
Gold leaf (backed with mica)	10·6	10·3
Palladium foil (saturated with hydrogen)	10·6	..
Gold leaf (lampblacked on reverse side)	7·3	..
Aluminium leaf (lampblacked on reverse side)	5·1	..

As metals move very slowly and do not come back to zero for a considerable time, satisfactory observations are not easily obtained. Except when testing precipitated silver, which was in fine powder, mica or pith disks were not employed as supports in this series. The gold leaf was not of the thinnest, but sufficiently thick to bear handling, weighing half a grain per square inch. The silver, platinum, and aluminium leaves were about double the thickness of the gold. The iron and palladium were thicker still.

The Table does not show any general relationship between the metals which I have tried, but before drawing conclusions, a much larger series of experiments should be undertaken. The extra weight of metallic disks prevented much experiment in this apparatus, but I hope to continue the experiments with metallic surfaces in an apparatus specially adapted to them. One or two points are here worth notice. The considerable movement of metallic iron with no screen interposed, and the slight action behind a water screen, show that the invisible heat rays are those chiefly absorbed by this metal; whilst the greatly increased proportional action on gold behind the water screen shows that with this metal, the luminous rays are more absorbed than the invisible heat rays.

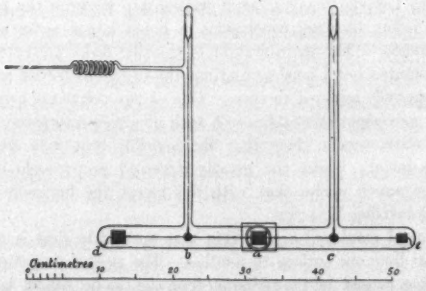
The films of metal employed are so thin that very little time is occupied in the conduction of heat from one surface to another. The rise of temperature, therefore, on the front surface, caused by the radiation from the candle, cannot be much greater than that on the back surface; and the resulting molecular pressure must exert itself on each side of the plate, the movement of repulsion being due to the difference of this pressure in favour of the front surface. Backing the metallic leaf with a thin plate of mica, by stopping the action of the molecular pressure on the reverse side, and throwing it all on the front, should therefore increase the amount of repulsion.

This reasoning is confirmed by the behaviour of the aluminium and platinum, but not by the gold, which is diminished in action by the mica backing. Gold, however, is seen to be acted on but little by the heat rays, and it is probable that these are the rays which most readily raise the temperature of the plate and cause molecular pressure to be exerted from the hinder surface. According to the same theory, if the transference of heat from the back surface be assisted by coating it with lampblack, the repulsion by rays falling on the unblacked surface should diminish. This is seen to be the case with aluminium and gold. The following Table will explain these actions :—

Metallic Plate.	Backing.		
	None.	Mica.	Lampblack.
Aluminium	13·8	28·7	5·1
Platinum	20·1	28·7	..
Gold	19·3	10·6	7·3

The following experiment proves that when radiation from a candle falls on the surface of a metal plate, heat rapidly passes through and causes molecular pressure to be exerted from the back of the plate. A torsion apparatus was made similar to those used so frequently in these experiments but having a double suspension, and

Fig. 3.



two independent beams, as shown in fig. 3, each supported by a glass fibre, and having at each end a plate of platinum. In the centre of the tube, at a, is a plate glass window, through which radiation falls on the plate at the end of the beam b, which plate, being larger than the one at the end of beam c, and overlapping it entirely, cuts off direct radiation from it. Stops d and e, at the outer extremities of the beams, prevent

them moving so as to touch where they overlap in the centre. At the centre of each beam is a mirror, by means of which a luminous index is reflected to a scale, so as to render evident any movement of the beams. The instrument being in adjustment, light from a candle is allowed to fall on the large plate of platinum at the a end of beam b. Almost instantly the motion of the index ray of light from the mirror c shows that the smaller plate of platinum attached to the other beam, a e, is driven backwards, in the same way as it would be had the large plate in front of it been transparent instead of opaque. The beam a d is prevented from pushing the hinder plate at a by the stop at d.

233. The action on the palladium saturated with hydrogen is lower than might be expected. The saturation was effected by making the metal the negative electrode of a three-cell Grove's battery, decomposing water acidulated with sulphuric acid. After action had gone on for about half an hour, the palladium was washed, dried with a cloth, and introduced into the apparatus. During exhaustion it is possible that a little hydrogen might have escaped from the metal, but the loss could not have been great, as the rate of exhaustion was not materially reduced. When the proper exhaustion was reached, no escape of the gas from the metal was noticed, the gauge remaining stationary. It was thought possible that, on allowing radiation to fall on the palladium-hydrogen plate in the vacuum, the repulsion might be accompanied by a liberation of hydrogen. I could not, however, detect any action of this kind, either by a depression of the gauge or by a diminution in the sensitiveness of the other disks to the radiation, which would have occurred had hydrogen escaped into the vacuum. Moreover, it is probable that had the action of incident radiation been accompanied by a liberation of hydrogen, the repulsion would have been stronger than it actually was. On testing the palladium plate after removing it from the apparatus, it was found to be abundantly charged with hydrogen.*

234. TABLE X.—Silver Salts.

	No screen.	Water screen interposed (5 millims.).
	*	*
Lampblack (standard disk)	100·0	100·0
Silver bromide	31·0	31·6
Silver chloride	20·9	14·7
Silver iodide, insensitive to light	20·9	9·2
" " sensitive to light, washed . .	18·1	20·0
" " " " not washed .	11·6	1·5

The silver salts were prepared by double decomposition in a room feebly lighted by orange light. They were well washed on the filter, and then divided into two portions; to one was added a dilute solution of the precipitating salt (potassium iodide or bromide, or sodium chloride), and to the other a dilute solution of silver nitrate.

* This persistence of the palladium-hydrogen alloy was discovered by Graham. See Proc. Roy. Soc., June 11, 1868, vol. xvi. p. 422; or Collected Works, p. 284.

Silver chloride, precipitated in the presence of a slight excess of sodium chloride, and subsequently washed, is a white powder which slowly darkens to a slate colour when exposed to daylight. When the precipitation takes place in the presence of an excess of silver nitrate, the chloride darkens more rapidly on exposure to light, and the depth of colour depends in great measure on the amount of free silver nitrate left with the silver chloride, and not subsequently washed out.

Silver iodide varies in colour according to the mode of preparation. If the potassium iodide is in excess, the silver iodide falls as a very pale yellow, almost white, precipitate; whilst, if precipitated in the presence of an excess of silver nitrate, it is of a decided straw-yellow colour. In the former case, it is not visibly affected by exposure to light, even to the sun. But the straw-yellow iodide formed in the presence of excess of silver salt is very sensitive to light. This sensitiveness is not rendered evident by much change of colour, since exposure to full day or even sunlight only causes it to change to a pale brown colour. If the *sensitive* silver iodide is exposed for one or two seconds to daylight, and then brought into a room faintly illuminated with orange light, no change of colour is visible; but on pouring over it a mixture of silver nitrate and a reducing agent, immediate blackening takes place, showing that a very strong, although invisible, change has been produced in the silver iodide by the momentary exposure to light.

In its behaviour to light, silver bromide may be considered intermediate between silver chloride and iodide. Its visible darkening, when exposed to daylight, is much less than that of silver chloride; whilst it also shares with the silver iodide, although in a less degree, the power of assuming a *latent* change capable of subsequent development. In all cases the presence of free silver nitrate increases the sensitiveness to light, and as this salt is washed away the sensitiveness diminishes. The rays of light which produce this photographic action are chiefly the indigo and violet rays, the red, orange, and yellow having no action. The most sensitive salts of silver can therefore be safely prepared in a room illuminated by a candle shining behind orange glass.

I experimented with all varieties of the three silver salts. They were dried, then ground up with pure water to a paste, and carefully painted on disks of mica, as described at par. 222. In the case of the silver bromide and chloride (prepared in the dark, and not exposed to light before the standard candle of the apparatus shone on them), no material difference of action could be observed between the sensitive and non-sensitive varieties. The figures in the table are therefore the mean of all the results, which were fairly concordant. With the silver iodide, however, the case is different: the almost white, insensitive variety is most affected; next comes the sensitive variety, from which, however, much of the free silver nitrate has been washed, so as to considerably reduce the sensitiveness. Lastly comes the silver iodide most sensitive to light; this is less affected mechanically by radiation than any other powder hitherto tried. The incident radiation from the candle, instead of causing molecular pressure on the surface, and driving back the silver iodide,

spends itself in chemical action, and causes a molecular change to take place in the structure of the silver iodide. When no latent change is produced, mechanical action is represented by 20·9; on slight latent change, the mechanical action is 18·1; but when strong latent disturbance in the molecular structure of the silver iodide is caused by the incident radiation, the mechanical action sinks to 11·6. The amount of repulsion behind a water screen, as shown in the second column, corroborates this reasoning as far as the non-sensitive and the most sensitive varieties of silver iodide, but it fails in the intermediate case. For this anomalous action I am unable to account.

235. The same series of silver salts which are given in Table X. were now subjected to further experiments. Without removing them from the apparatus, or interfering with the adjustment, the disks were first exposed for one minute to the light of burning magnesium, and then faint sunlight was reflected on to them for two minutes; owing to the direction along which the ray had to pass, three reflections were necessary. After each of these exposures to light, the apparatus was completely closed up and kept in darkness till the molecular disturbance induced by the light had passed off. Experiments were then tried with a standard candle in the usual way, and the amount of repulsion of each disk recorded. Lastly, air was let in, the disks were carefully lifted out of the tube by the flat glass fibre on which they were cemented (222) and exposed to bright daylight for half an hour; all the disks except the insensitive silver iodide were visibly darkened. They were then re-introduced into the apparatus, the whole was exhausted, and the experiment repeated. The results of these experiments are given in the following table:—

TABLE XA.—Silver Salts after Exposure to Light.

	Original repulsion before exposure.	Repulsion by candle light after exposure to			
		Magnesium light.	Faint sun.	Daylight.	
				Without screen.	Behind water screen.
Lampblack (standard)	100·0	100·0	100·0	100·0	100·0
Silver bromide	31·0	33·0	35·1	58·7	88·8
„ chloride	20·9	21·0	24·3	69·8	98·1
„ iodide, insensitive	20·9	19·9	20·0	23·0	12·3
„ „ sensitive, washed	18·1	19·0	23·2	27·3	40·1
„ „ sensitive, not washed	11·6	22·6	29·8	38·5	75·5

This table shows very clearly how readily a change in the state of the surface is detected by an increased amount of repulsion under the influence of radiation. With the exception of the insensitive silver iodide in the second column (probably due to unavoidable errors of experiment), every exposure to light has left the silver surface in a condition more sensitive to radiation. The silver chloride, which darkens

most by light, is ultimately most repelled, whilst the bromide follows next in sensitiveness. As might be expected, the insensitive iodide is less acted on by light; the washed sensitive iodide is little affected by the magnesium light, and never attains any great sensitiveness to the mechanical action of radiation. The most sensitive silver iodide has its capacity for molecular change almost exhausted by the first exposure to the light of burning magnesium, and after the sudden jump from 11·6 to 22·6, is comparatively little affected by subsequent exposure to daylight or sunlight.

236. TABLE XI.—Selenium, Crystalline and Vitreous.

	No screen.	Water screen interposed (5 millims.).
	*	*
Lampblack (standard disk)	100·0	100·0
Selenium disk, crystalline, No. 1	21·1	18·6
„ „ „ No. 2	19·1	17·0
„ „ vitreous	15·0	..

The selenium disks were suspended direct in the apparatus, without being attached to mica or pith disks as were the previous substances experimented upon. They are 17 millims. diameter, and about 0·5 millim. thick. The disks were kindly prepared for me by Mr. R. J. MOSS, who, in conjunction with Mr. H. N. DRAPER, has been for some time investigating the action of light on selenium in different physical states.* Disks of vitreous selenium were first prepared; they were heated for one hour to 100° C., and then for one hour to 210° C., which left them in the condition in which Mr. Moss and Mr. DRAPER find selenium most sensitive to *light* action. Two disks of crystalline selenium thus prepared were experimented with; and at the same time a third disk of selenium, in its ordinary vitreous condition, was exposed in the apparatus for purposes of comparison.

Mr. Moss finds† that exposure of selenium in a Sprengel vacuum causes it to acquire a film of mercury selenide, which increases its conducting power for electricity. As it was likely this alteration might cause the molecular disturbance on the surface of the selenium, under the influence of radiation, to vary, extra care was taken to keep the vapour of mercury from penetrating to the selenium by interposing between the pump and the apparatus additional tubes filled with sulphur, copper, and closely packed gold leaf (355).

When the crystalline selenium was under experiment, an effect already noticed in previous cases was very marked. On cutting off the light, and watching the index ray in its passage across the graduated scale, it was observed that the ray did not readily return to zero. Experimenting many times in rapid succession, this sluggishness could be accumulated. In other instances in which this action has been noticed, I

* 'Proceedings of the Royal Irish Academy,' vol. i., ser. ii. (Sci.), p. 529.

† 'Proceedings of the Royal Society,' May 11, 1876, vol. xxv. p. 22.

explain it by the fact that the disk is a very bad conductor of heat; consequently the molecular disturbance is retained on the front surface, and does not sink so rapidly as it would were the heat rapidly conducted through to the other side of the disk. In the case of the crystalline selenium this action is very strongly marked, and without denying that some of the sluggishness to return to zero may be due to the bad conducting power of selenium for heat, the greater portion of this action is explained by the fact of the sensitiveness to light of this form of selenium. It would seem as if the impact of light on the surface produced a persistent disturbance, which keeps up a similar disturbance in the adjacent gaseous molecules, and takes some time to subside. It is known that the change in electric conducting power of crystalline selenium, when it is transferred from light to darkness, takes some time to effect.

The vitreous selenium does not show this strongly marked sluggishness to return to zero, and it is decidedly less acted on by radiation. This may be due to its non-sensitiveness to light, or to its shining surface reflecting more of the candle rays than does the crystalline surface.

237. TABLE XII.—Miscellaneous Substances—Pith, Mica, Charcoal, Glass, &c.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Pith, plain white	17·7	0·4
Pith, lampblacked on one side, white side exposed	0·0	0·0
Amadou, lampblacked on one side, black side exposed	57·5	53·6
Amadou, lampblacked on one side, white side exposed	21·0	12·2
Amadou, not blacked	20·5	7·6
Mica, silver flake, lampblacked on one side, black side exposed	151·0	125·5
Mica, roasted, blacked on the opaque side, black side exposed	111·7	89·3
Mica, roasted, blacked on the clear side, black side exposed	87·5	78·5
Mica, silver flake	12·5	2·1
Mica, roasted, clear side exposed	6·7	0·0
Mica, roasted, blacked on clear side, black turned away from light	6·8	3·5
Mica, roasted, blacked on opaque side, black turned away from light	7·6	8·9
Mica, silver flake, blacked on one side, black turned away from light	9·8	8·8
Charcoal, wood, parallel to the grain	18·4	14·7
Charcoal, wood, across the grain	15·2	10·7
Charcoal, cocoa-nut shell	11·6	3·7
Microscopic glass, quite clear	6·5	0·5
Microscopic glass, having the portion of the glass tube behind it coated internally with lampblack	6·0	0·0

The complicated nature of these actions is well shown by an examination of the results given in the first three lines. Lampblack on a pith disk being 100, plain white pith without any lampblack is 17·7. But when lampblack is applied to the back of the pith, and the plain white surface is again exposed to radiation, the action sinks to zero. The repulsion exerted on the white pith must be the same in each case, but the presence of lampblack behind it has caused an absorption of heat by the back surface, producing molecular pressure just sufficient to neutralise the pressure in front. It is not sufficient therefore to take into account the kind of powder exposed to radiation; its conducting power for heat, as well as that of the disk which serves to support it, and the absorbing and radiating powers of the back surface for heat, together with its distance from the bounding surface of the glass vessel, all have to be taken into consideration. For these reasons too much weight must not be attached to the results given in the foregoing tables. They convey a fair general idea of the variations in the power according to the colour and physical condition of the substances exposed to radiation, and considering the enormous difficulty in getting results which have any approach to quantitative accuracy, they are very satisfactory; but it must be remembered that they are only comparable one with another under the exact conditions in which they were tried, and it is not unlikely that a repetition of the series, with an alteration in some apparently unimportant item, such as an increased diameter of glass tube, a thicker disk of pith, or the substitution for pith of a substance which will better conduct heat, might give a different series of numbers. The proportion between them, however, would probably remain the same as at present.

In an ordinary radiometer, such as I described in my last paper on this subject, (145), the disks are of pith, lampblacked on one side. The present results show that the whole of the force of radiation exerted on the black surface is utilised in turning the fly round.

238. The experiments were tried with mica to test a suggestion by Professor STOKES, that roasted mica, lampblacked on one side, would combine in a pre-eminent degree the conditions needed for the fly of a radiometer, namely,—

1. Good absorption on one face.
2. Good reflection on the other, for heat as well as light.
3. Bad conduction.
4. Absence of organic matter.
5. Extreme lightness.

I had already used mica both plain and roasted, but had never tested them systematically. The "silver flake" mica is a natural mineral occurring in the United States. It is of a brilliant silvery lustre, and splits into exceedingly thin fibres, which are as coherent and tough as ordinary mica, whilst they have the bright reflecting surface of mica artificially calcined. The mineral is probably produced

from ordinary clear mica, through the agency of volcanic or other natural heat. The results show how well Professor STOKES's theoretical reasoning is confirmed by experiment. With a radiometer, the fly of roasted mica lampblacked on one side, the power of radiation to cause rotation will be 111·7 on the black, and −7·6 on the white side, or a total of 119·3, as against 100 with lampblacked pith. The employment of silver flake mica is still more advantageous, as here the blacked side is repelled with a force of 151, whilst the bright side is (apparently) attracted with a force of 9·8, making a total force to turn the fly round of 160·8. The negative action, or apparent attraction, seen when radiation falls on the clear face of a mica disk lampblacked behind, is caused by the heat passing through the thin plate and warming the hinder surface of lampblack. The thinner the mica the greater is this action, up to the point when the lampblack begins to show through. With a thick piece of silver flake mica no negative repulsion takes place, but it becomes positive, increasing in power until it reaches 12·5, which is the amount given by silver flake mica with no black behind it. Taking the action on the blacked silver flake mica as 151, and that on the same mica unblacked as 12·5, the action exerted on the black surface is seen to be 12 times greater than that on the white surface. In some experiments on roasted mica radiometers, published by Professor E. WARTMANN,* the action on the black face is found to be 11·9 times stronger than that on the white face.

On heating clear mica in the blowpipe flame, the side on which the flame plays becomes opaque and silvery, whilst the other side retains its glassy reflecting surface. The employment of one or the other side as the lampblacked surface exerts a considerable difference on the results.

239. The very low results given by the three kinds of charcoal I explain thus:—Radiation falling on the front surface is absorbed and converted into thermometric heat (107, 195), which warms the front side of the charcoal. Although charcoal is one of the worst known conductors of heat, there is no doubt that the vibration caused by heat on the surface of a plate of charcoal is quickly communicated to the layer beneath, and thus a very short time suffices for the conduction of heat through a disk only half a millimetre thick. Having arrived at the hinder surface, the heat which there becomes sensible causes negative repulsion to take place, as in the case of the roasted and blacked mica (238), and the numbers 18·4, 15·2, and 11·6 are simply the differences between these two opposing actions.

This explanation is proved by an experiment. A reference to Table XII. shows that the action of radiation on plain pith is equal to 17·7, whilst that on cocoa-nut shell charcoal is only 11·6. Now were this amount of 11·6 the total action of radiation instead of the difference only, lampblacking the front surface of the charcoal should bring it up to 100, and a radiometer made of cocoa-nut shell charcoal lampblacked on one side should work better than one made of lampblacked pith. On making such an instrument it was however found to be almost insensitive, the feeble

* Société de Physique et d'Histoire Naturelle de Genève, Séance du 2 Mars, 1876.

rotation produced being simply due to the slightly superior absorption which the lampblack possesses over the solid surface of charcoal.

240. The experiments with clear microscopic glass, given in Table XII., were tried in order to test the theory advanced in my paper of Feb. 5, 1876 (194, 195), that the "apparent viscosity of a vacuum"* was due to the absorption, and subsequent slow communication of heat from the substance on which the light fell to the adjacent gaseous molecules. That this effect does occur to an appreciable extent has been proved by the results obtained with aluminium and gold backed with lampblack (232), and with mica and pith backed with lampblack (237). Mr. JOHNSTONE STONEY suggested that this might be tested in a different way by coating the inner side of the exhausted tube with lampblack opposite to the disk of glass. Upon allowing light to fall across the vacuum on this blackened surface, the disk should move towards the light. The results show that such an action does not take place to an appreciable extent. Being fully convinced that the theory is correct, I have carefully examined the apparatus, and thought over the conditions under which the experiment was tried, in the hope of discovering the cause of the anomaly and thereby reconciling this result with the numerous array of proofs ranged on the opposite side. I think a sufficient explanation is to be found in the behaviour of the glass disk when it is exposed to radiation behind a water screen. When the total radiation from the candle falls on the thin glass, both the light and heat are acting, and the movement of 6·5 may be due to either of these or to both combined. By interposing a water screen I practically cut off all the invisible heat rays, and any action which now takes place must be due to the luminous rays. But behind water the repulsion is only 0·5, in comparison to lampblacked pith behind water =100, or not more than (0·5÷12=) 0·04, in comparison to the repulsion of 6·5 when the water screen is away. The luminous rays are therefore 162·5 times less active on thin glass than are the heat rays, and may consequently be left out of consideration altogether; they pass through

* This must not be confounded with the *viscosity of the residual gas*, in the sense in which I speak of it in the preliminary notice published in the 'Proceedings of the Royal Society,' No. 175, 1876. What I meant by the "apparent viscosity of a vacuum," spoken of in par. 195, is rendered clear by the description of the experiment, which I will quote from par. 194:—"A candle held close to the screen, and the shutter momentarily opened and closed, sent the index with some violence to the extreme limit of the scale. It then slowly came back to zero, and there stopped. . . . . The movement of the beam . . . . . seemed as if it were held in check by a force acting the whole time of its movement, and not only for the time the light acted. The impression conveyed was that the beam was swinging in a viscous fluid. . . . . I then gave the apparatus a sudden twist round, so as to cause the beam to knock against the side of the tube. This set it swinging through a large arc, and the oscillations kept up with perfect freedom for several minutes, declining in amplitude at each oscillation, till the beam ultimately came to zero. This perfectly free movement is in strong contrast to the constraint under which the beam moves when the initial blow is given by a ray of light instead of by a mechanical push."

In an earlier experiment of the same kind, described in Part II. of this research, I express the same idea thus:—"(107.) This behaviour points to the return movement taking place under the influence of a force which remains active after the original radiation is cut off, and which is only gradually dissipated."

the glass unchanged, and can therefore do no work on its surface. With the ultra-red heat rays, the case is different; to these glass is almost opaque, and their energy, being arrested, is transformed into thermometric heat, or heat of temperature which raises the temperature of the glass. But before arriving at the disk of thin glass under experiment, the radiation from the candle meets the obstruction offered by the front wall of the glass tube in which the disks swing. The heat rays from the candle are mostly stopped by this glass and raise its temperature. The warm glass then becomes the point whence the lines of molecular pressure radiate; and it is this molecular force which repels the plate of thin glass, and not the reaction of molecules which are set into activity by a rise of temperature of its own surface. The luminous rays from the candle pass unchanged through the front wall of the tube, through the thin glass disk, and strike the lampblack with which the hind wall is coated. Here they are quenched, and, as I think has been sufficiently proved, they increase the temperature of the lampblacked surface and cause molecular pressure in the adjacent gas. The disk of thin glass suspended in the centre of the tube is therefore acted upon by two opposing forces, one from the front and one from the back wall of the tube, and its movement is in accordance with the stronger of the two. The front force is due to the direct heat of the candle, whilst the back force is due to the light falling on the lampblack and being degraded into heat. Were the heat and the light originally equal in amount, the original heat would ultimately largely exceed that produced from the degraded light; but, as is already proved (197), much of the action of a candle is due to the ultra-red rays, and it may therefore be reasonably supposed that, in comparison to the strong action of the repulsion from the front wall of the tube, that from the back of the tube is inappreciable. That such an action as is here sought really occurs is abundantly proved further on, but the present form of apparatus is not suitable for showing it.

ACTION OF SCREENS.

241. When the experiments described in the foregoing paragraphs were first commenced, I used several screens besides water (109, 200, 201), and tabulated the results with each kind. They consisted of plates of glass of various colours, and glass cells filled with coloured solutions, such as potash bichromate, copper sulphate, iodine dissolved in carbon disulphide, &c. But the time required to take a sufficient number of observations in order to get a satisfactory mean with each substance tried behind each screen, was more than I could give; I was therefore obliged to content myself with a single screen. For several reasons I decided upon water in a clear glass cell. First, it is almost perfectly opaque to the invisible heat rays, consequently its employment facilitates discrimination between actions due to heat and to heat and light combined. Secondly, it is colourless, and, having no selective action on any visible ray of light, can be used in conjunction with any coloured

powder, without complicating the results. Coloured glasses, or very thick masses of colourless plate glass, generally act in proportion to the amount of light they apparently cut off; whilst coloured solutions act like water, with a special action superadded, due to the colour. A very considerable thickness of glass offers less obstruction to the motion-producing rays than does a very thin layer of water. A clear plate of alum is very similar to water in its effects, and a solution of alum is almost identical with the same thickness of water. Copper sulphate solution offers great obstruction when artificial light is used. These facts show that glass is not so opaque to the ultra red heat rays as is water; that the lowest visible red rays are likewise powerful heat rays; and that by cutting off these also, by adding copper sulphate to water, a considerable fraction of the rays which produce repulsion when artificial light is used will be cut off.*

Seeing the very strong absorptive action which gaseous ammonia exerts on rays of radiant heat,† as measured by a thermo-pile, I endeavoured to detect any diminution in the intensity of the repulsion on pith, lampblacked and plain, lampblacked mica, as well as on other bodies, when the rays from the candle were allowed to pass through a layer of pure ammonia gas, 6 inches in thickness. I was, however, unable to detect the slightest diminution of action which could be ascribed to the absorption of heat by the ammonia gas (200).

DIFFERENT ACTIONS OF RADIANT HEAT AND OF LIGHT.

242. An examination of the preceding tables shows that the substances used in experiment can be divided into two classes: 1, *negative*, those in which the repulsion behind water is greater, in proportion to the standard, than when no screen is present; and 2, *positive*, those in which the repulsion, in proportion to the standard, is less behind water than when no screen is interposed. From these tables a few illustrations are selected:—

TABLE XIII.

CLASS 1.

	No screen.	Water screen.	Difference.
Lampblack (standard disk)	100·0	100·0	0·0
Copper tungstate	51·2	77·0	−25·8
Saffranin	41·0	52·5	−11·5
Precipitated selenium	35·8	69·5	−33·7
Copper oxalate	30·1	40·2	−10·1

* In some rooms lighted by gas, a layer of water is interposed between the light and the lower part of the room, with the view to cut off the heat. This device answers very well, but the absorption of heat could be greatly augmented by adding to the water a very little copper sulphate, whilst the colour of the light would at the same time be improved.

† 'Contributions to Molecular Physics in the Domain of Radiant Heat.' By J. TYNDALL, LL.D., F.R.S., p. 80.

CLASS 2.

	No screen.	Water screen.	Difference.
Lampblack (standard disk)	100·0	100·0	0·0
Chromic oxide, pale green	71·5	20·2	+51·3
Persulpho-cyanogen	43·9	11·5	+32·4
Hydrated zinc oxide	40·5	14·0	+26·5
Barium sulphate	37·4	4·2	+33·2
Calcium carbonate	28·5	3·9	+14·6

In class 1, the behaviour behind water shows that the substances experimented on are much more affected by light than by invisible heat; whilst the behaviour of the bodies in class 2, behind water, shows that these are much more acted on by the ultra-red heat rays than by the luminous rays. To render these differences of action more comparable, the figures in the second column (water screen) must be divided by twelve (par. 224). Uniting the two classes together, the figures then become as follows:—

243. TABLE XIV.

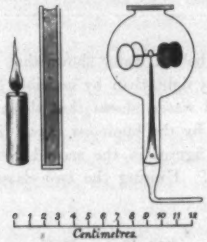
	No screen.	Water screen interposed (5 millims.)
Lampblack (standard disk)	100·0	8·3
Chromic oxide, pale green	71·5	1·7
Copper tungstate	51·2	6·4
Persulpho-cyanogen	43·9	1·0
Saffranin	41·0	4·3
Hydrated zinc oxide	40·5	1·2
Barium sulphate	37·4	0·3
Selenium, precipitated	35·8	5·8
Copper oxalate	30·1	3·3
Calcium carbonate	28·5	0·3

EXPERIMENTAL VERIFICATION OF THEORY.

244. At the end of a long investigation with complicated apparatus, it is a great satisfaction to find that an easy way of proving the general accuracy of the results offers itself; more especially if the numerical results show many discrepancies, which may be due to errors of experiment, or on the other hand may be anomalies, pointing in the direction of further discoveries. A glance at the above table shows that the results can be proved by balancing one powder against another in a radiometer. A bulb was blown on the end of a wide tube, as shown at fig. 4. The top of the bulb was opened and turned over to form a lip; this was ground smooth and polished so as to be readily closed by cementing on it a piece of plate glass. A glass stem supports a fine

needle in the centre of the bulb, and on this rests a glass cap, to which is attached four radial arms of aluminium. To these arms disks of mica or pith can be fastened, so as to form the moveable fly of a radiometer. The disks can be changed by uncementing the glass top, and lifting the fly out with tweezers. The lower part of the

Fig. 4.



tube is drawn out for connexion with the mercury pump. The powders used for experiment were carefully painted on the opposite sides of pith or mica disks, only water or alcohol being used (222).

245. The first pair of substances tested in this apparatus were chromic oxide and precipitated selenium.* In a tabular form, these stand as follows (243) :—

	No screen.	Water screen.
Chromic oxide	71·5	1·7
Selenium, precipitated	35·8	5·8
Difference	+35·7	−4·1

A radiometer therefore made of these powders, on alternate sides of pith disks, should rotate in one direction when no screen is interposed between it and the light, and in the opposite direction when behind a water screen—the positive rotation taking place with a force of 35·7, and the negative rotation with a force of 4·1.

When the apparatus was exhausted up to the point of maximum sensitiveness, a glass cell full of water was placed in front of it and a lighted candle brought near. Negative rotation immediately commenced, the selenium being repelled. On drawing away the screen the rotation stopped, and positive rotation commenced, which could

* The selenium was precipitated as a brilliant scarlet powder, by boiling commercial selenium in fine powder, in solution of cyanide of potassium, and then supersaturating with hydrochloric acid. Selenocyanide of potassium is formed, and I showed in 1851 that this salt is decomposed by almost any acid, with precipitation of selenium. (Chem. Soc. Journ., iv., 1852, p. 13.)

be changed to negative by interposing the water screen. The positive rotation was much the stronger of the two.

Exposed to the candle radiation behind a screen of black talc, perfectly opaque but diathermous, positive rotation ensued.

The candle was removed, and a hot glass shade* put over the bulb and fly. Negative rotation took place; on removing the hot shade and letting the instrument cool, there was no reversal of rotation (161, 165, 167, 168).

246. The fly was then removed from the apparatus, and the pith-disks replaced by others coated on opposite sides with the following powders :—

	No screen.	Water screen.
Chromic oxide	71·5	1·7
Copper tungstate	51·2	6·4
	+20·3	−4·7

When properly exhausted, the instrument was exposed to candle light behind a water screen, as in the previous experiment; quick negative rotation took place, the copper tungstate being repelled. Whilst the fly was in full rotation, the water screen was drawn away, the candle still remaining; the negative rotation got slacker and slacker till the fly just moved round, but it did not stop entirely, or revolve positively, as it should have done according to the indications of the above table. By holding a second candle, temporarily, close to the chromium side of a disk, the movement could be stopped, but on taking away the second candle the slow negative rotation recommenced. So far, the results only half agree with theory: the negative rotation behind water is correct, but the positive rotation to the direct light is not seen. The candle was then removed, and the fly allowed to come to rest. When quite still and cold, the lighted candle was again brought up to the apparatus, when the fly at once moved, the chromic oxide being this time repelled, and positive rotation, in accordance with theory, keeping up for several revolutions. After a little time, however, the positive rotation slackened, then stopped altogether, and finally gave place to a very slow negative rotation.

From these experiments it appears that the superior repulsion, exerted by radiation from a naked candle, on chromic oxide over copper tungstate, is due to the former being more sensitive to ultra-red heat rays: this, in fact, is in accordance with the results behind water. When dark heat rays are thus filtered off, the copper tungstate is four times more sensitive to the residual luminous rays than is the chromic oxide. But the peculiar behaviour in the last experiment carries the proof a step further. The candle, shining on the glass bulb, gradually raises its temperature, and the glass begins to radiate dark heat in all directions, on the chromic oxide and copper tungstate

* A hot glass shade is used as a convenient means of heating the bulb, by immersing it in a hot air bath, without the liability of introducing action of rays other than those emitted by hot glass.

equally. Now, I have already shown (128, 144, 155, 156, 157, 161) that dark heat, radiated from glass, has a very different action on a lampblack and pith radiometer from that of the luminous rays; and at pars. 170, 171, 172, reasons are adduced for believing that, to rays of low refrangibility radiated from hot glass, white pith and lampblack change places, the pith becoming black and the lampblack acting as a light substance.

It is therefore legitimate to carry out the same line of reasoning in the case of chromic oxide and copper tungstate. To the total radiation from the candle, unfiltered except through the thin glass wall of the bulb, the chromium compound is the more sensitive; the chromic oxide is black, and the copper tungstate white. But when exposed to the heat rays of low refrangibility emitted by warm glass, the two powders change places, and chromic oxide becomes white, whilst copper tungstate absorbs them powerfully, and behaves as a black powder. The difference between the action of dark heat and that due to the other rays is sufficient not only to overcome the *plus* action of 20·3, but to give a slight negative action.*

When covered with a hot glass shade, negative rotation takes place, the copper tungstate being repelled; on removing the shade and letting the instrument cool, reverse rotation takes place, the fly now moving positively. The theory just discussed is therefore corroborated.

247. The next powders experimented with were persulpho-cyanogen and copper oxalate; in a tabular form these stand thus:—

	No screen.	Water screen.
Persulpho-cyanogen	43·9	1·0
Copper oxalate	30·1	3·3
	+13·8	−2·3

Showing a positive rotation of 13·8 to the naked flame, and a negative rotation of 2·3 behind a water screen. When properly exhausted and exposed to the candle behind water, negative rotation was produced, and continued steadily as long as the experiment was tried. Without moving the candle the water screen was now taken away. The direction of rotation instantly changed, and gave place to a rapid positive rotation. The speed, however, soon diminished, and in a little time, when the bulb had become warm, there was great difficulty in the copper oxalate passing the candle, and sometimes a disk would stop on the dead centre. A gentle tap on the bulb always sent it on, and then rotation would continue for a short time longer, the persulpho-cyanogen always being the powder most repelled by the naked flame.

When the fly was cold a hot glass shade was inverted over the bulb; positive rotation immediately commenced, which, when the hot shade was removed and the apparatus was cooling, changed to negative rotation.

* I may here remark that this anomalous action is strongly marked in the case of most copper salts, which act as if they were nearly white to light, but black to heat of low refrangibility.

The phenomena observed with this couple are similar to those commented on in the case of the chromic oxide and copper tungstate (246). The explanation there given will apply equally well to the present case.

248. Another couple was now tried, namely—

	No screen.	Water screen.
Persulpho-cyanogen	43·9	1·0
Saffranin	41·0	4·3
	+ 2·9	−3·3

Tested in the same way as the others the results were in conformity with the figures. Positive rotation (persulpho-cyanogen being repelled) was obtained when exposed to the naked flame, and negative rotation (saffranin repelled) when water was interposed. In either case the movement was feeble, and was not continuous with only one candle. With two or three candles the rotations were strong.

249. Another couple (saffranin and hydrated zinc oxide) were now selected, which were nearly equal to the naked flame but different behind water. The figures are—

	No screen.	Water screen.
Saffranin	41·0	4·3
Hydrated zinc oxide	40·5	1·2
	+ 0·5	+3·1

Tested as in the other experiments, no motion could be detected with the naked flame of one candle, and only slight repulsion of the saffranin when five candles were used. Behind water, however, there was good rotation with one candle, the saffranin being repelled.

Upon inverting a hot glass shade over the bulb no movement of the fly was produced.

250. A couple was now selected which should give rotation to the naked flame, but none behind water. They were—

	No screen.	Water screen.
Barium sulphate	37·4	0·3
Calcium carbonate	28·5	0·3
	+ 8·9	0·0

With no screen, good rotation was produced, the barium compound being repelled. No movement whatever was observed when a water screen was interposed.

Covered with a hot glass shade rotation was produced, the barium sulphate being repelled. There was slight reversion of movement on cooling.

251. The following couple—

	No screen.	Water screen.
Thallic oxide	121·7	9·2
Green platinum salt of Magnus	89·5	8·8
	33·2	0·4

also acted to the naked flame and behind water in accordance with theory, giving good rotation in one case and no movement in the other.

Covered with a hot glass shade the platinum compound was repelled, producing rotation. On removing the source of heat, and allowing the bulb to cool, reversion of movement took place.

252. In addition to these couples, experiments were also tried in the apparatus with other substances likely to give valuable results. Metallic iron and gold, rolled together to thin foil and well polished on each side, were punched into disks and mounted on the fly, the gold facing one way and the iron the other. After exhaustion the iron was most repelled by a candle flame, rotation being produced. When the bulb was grasped in the warm hand or covered with a hot shade the gold was repelled, producing rotation, which reversed on cooling.

253. Platinum and gold in thin foil, heated till the gold just fused to the surface of the platinum and then rolled flat, were tried in the same way. Exposed to the light of a candle the gold was slightly repelled, and with three candles continuous rotation was produced. Covered with a hot shade the platinum was slightly repelled.

254. Zinc and copper were rolled together and tried in the same manner in the apparatus. One candle gave good rotation, the zinc being repelled. Heated with a hot glass shade the zinc was still repelled, rotation being produced, and the motion reversing on cooling. Behind water no movement was produced by the light of three candles.

ANOMALIES EXHIBITED BY SELENIUM.

255. The most sensitive couple experimented on is the chromic oxide and scarlet selenium (245), and accordingly I put these powders together in the form of a radiometer both for the sake of further experiments and for the convenience of retaining the actual apparatus in a permanent form for future illustration or research. Thin pith was used for the disks, and the powders were thickly painted on alternate sides, so that the same powder should always follow or lead, according to the direction of rotation. The radiometer was well exhausted and then sealed off. The experiments are sufficiently instructive to warrant my giving them somewhat in detail, as they illustrate in a striking manner the extremely complicated actions involved in these repulsions, and also serve as a warning against hasty generalisations.

It should be remembered that the experiments collected together in this paper have extended over more than twelve months; each experiment was fully described

at the time in my note book, and it is my custom to verify everything of importance. The record of experiments given in paragraph 245 was written in May last. The repetition now described took place in October.

When a lighted candle was placed 1½ inches from the bulb continuous rotation was produced, but instead of the chromic oxide being repelled the selenium was repelled. Another candle was lighted, and the two only made the abnormal rotation stronger. After a time the bulb became warm and the rotation got slower till it stopped. The candles were blown out, and when the bulb had cooled, a water cell was interposed and one candle was lighted. Good rotation now took place in the same direction as when no water intervened; the radiometer, in fact, behaved just like an ordinary lampblack and white pith one, the scarlet selenium representing the black surface. The results were not quite so strong as when lampblack is used, but they were so definite that had it not been for the previous observations I should unhesitatingly have assumed that the true action was as now recorded. But knowing that my former results were just as carefully worked out as the present ones, and not admitting "experimental errors" as explanations of anomalies, I sought long and anxiously for a physical cause of these two diametrically opposite results. Every circumstance which could influence the result was the same in the two experiments, yet in May I found a candle repelled chromic oxide more than it did selenium, whilst in October I found the selenium decidedly the more repelled of the two, positive rotation occurring in one case and negative in the other.

256. Next day I repeated the experiment by placing a lighted candle near the radiometer, and the fly at once rotated, *the chromic oxide being repelled.* Nothing had been moved, nothing had changed since the previous day except the candle. Here was a clue which, followed up, explained everything. The candle used in May was a large wax candle, four to the pound; that used in October was a sperm candle of a smaller size, six to the pound, and having a whiter flame. I found I could always get the chromic oxide repelled by using the wax candle, and the selenium repelled by using the sperm candle; the difference between the two is evidently due to a variation in the proportion of light to heat. The sperm has a very white flame, whilst the wax candle burns with a yellower flame: for equal amounts of light, therefore, the wax candle gives more heat; and according to theory heat is principally required to repel chromic oxide, whilst light chiefly repels selenium. To test this by experiment was easy. A spirit flame was brought near the bulb; decided repulsion of the chromic oxide with quick rotation followed. A Bunsen burner, with the air holes covered (giving a luminous flame), brought near the bulb caused repulsion of the selenium, but scarcely strong enough to give continuous rotation. On uncovering the air holes and making the flame non-luminous the chromic oxide was strongly repelled, giving rapid rotation.

The radiometer was exposed to the light from two candles behind a transparent plate of alum, 5 millims. thick; continuous quick rotation ensued, the selenium being

repelled. A spirit flame was now brought up about six inches from the opposite side of the radiometer, nothing intervening. The rotation gradually slackened, and then stopped. On bringing the spirit flame nearer, the heat overbalanced the candle-light and the chromic oxide was repelled, whilst on removing the spirit flame further off the light overcame the heat, and the selenium was repelled. The balance between the heat from the spirit lamp and the light from the candles was perfect, the fly obeying the stronger force as delicately as if it were a magnetic needle under the influence of two opposite currents.

257. The very strong action exerted by solution of copper sulphate on the rays which are usually most powerful in causing repulsion in a vacuum, has already been mentioned (139, 153, 241). The radiometer was exposed to the light of the same two candles, a cell containing a saturated solution of copper sulphate, 5 millims. thick, being interposed; rotation in this case was also produced, the selenium being repelled with a force only a little less than it would have been behind water or alum.

A colourless gas flame from a Bunsen burner was coloured intensely green by thallium, and the radiometer brought near it. To the eye, by this light, the chromic oxide looked nearly white, and the selenium black. The rotation due to the repulsion of the chromic oxide was, however, apparently as strong as when the non-luminous flame was used. This is a proof that the train of argument I have employed on former occasions is correct—viz., that certain substances have an opposite absorptive action on rays of dark heat to what they have on light, and that an optically white body may be thermically black, and *vice versâ* (170, 171, 172, 246). Here, for instance, chromic oxide is optically white and thermically black, whilst scarlet selenium is optically black and thermically white.

258. The experiments with the Bunsen flame show that the behaviour of scarlet selenium in a vacuum is closely allied to the variations in the electrical resistance of crystalline selenium when exposed to similar flames. During some researches undertaken to determine whether the change in the electrical resistance of selenium is due to radiant heat, light, or chemical action, Professor W. G. Adams* tried the effect of exposing the selenium to a Bunsen burner alone, in its ordinary state, and when it is rendered luminous by stopping the air holes. I quote the following passages from his printed paper:—

"Exposure to the ordinary Bunsen flame for several seconds only caused a slight deflection of about 10 divisions of the scale.

"On making the flame luminous, the needle was suddenly deflected off the scale with great rapidity.

"With the 10 shunt to the galvanometer, there was no deflection on exposure to the ordinary Bunsen flame; but with the luminous flame there was a sudden deflection, which increased to 250 divisions of the scale in a few seconds.

* "On the Action of Light on Selenium." Proc. Roy. Soc., June 17, 1875, vol xxiii. p. 535.

"The illuminating power of these sources of light was compared by means of the Bunsen photometer.

"The light of the ordinary Bunsen flame could scarcely be measured, but was somewhere about $\frac{1}{100}$th part of a candle, and of the luminous Bunsen flame about 10 candles.

"The heating effects of these sources were compared by means of the thermo-electric pile and delicate astatic galvanometer.

"At a distance of one foot from the face of the pile, the deflection produced by the ordinary Bunsen flame was $46\frac{1}{2}°$, and by the luminous Bunsen flame was 52°.

"These experiments clearly show that very little effect is produced by the radiation of obscure heat, but that the effect is due almost entirely, if not entirely, to light.

"These experiments show that the action on the selenium is due principally, if not entirely, to radiations belonging to the visible part of the spectrum."

These passages might almost have been written by myself to describe the repulsion produced by obscure and luminous radiation on scarlet selenium, so closely do they express the actions which I have been elucidating.

259. Professor ADAMS concludes his paper by suggesting two hypotheses as possible explanations which may help as guides in further experiments, but which he thinks cannot be accepted as proved without further evidence. These hypotheses are :—

(1.) That the light, falling on the selenium, causes an electro-motive force in it, in the same direction as the battery-current passing through it, the effect being similar to the effect due to polarization in an electrolyte, but in the opposite direction.

(2.) That the light, falling on the selenium, causes a change on its surface, akin to the change which it produces on the surface of a phosphorescent body, and that in consequence of this change the electric current is enabled to pass more readily over the surface of the selenium.

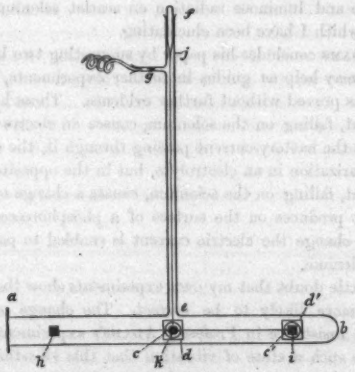
I think there is little doubt that my own experiments show that the second of these two hypotheses is more likely to be correct. The change on the surface, which diminishes electrical resistance in Professor ADAMS's experiments, sets the molecules of the selenium into such a state of vibration that this vibration is communicated to the adjacent molecules of residual gas, and causes them to exert molecular pressure, which drives back the selenium. In comparing the two series of experiments, it must be borne in mind that in testing plates of crystalline selenium which were in the state most sensitive to light from Professor ADAMS's point of view (236), I failed to detect any special action; whilst the variety of selenium found to be most sensitive to the luminous rays is a scarlet, amorphous powder, precipitated from a cold solution, and very different, physically, from the crystalline variety produced by long continued heat on the ordinary vitreous selenium.

EXPERIMENTS WITH POLARISED LIGHT.

259. I have long endeavoured to carry out a suggestion made by Professor MASKELYNE during the discussion of the first part of my paper "On Repulsion resulting from Radiation," at the Royal Society, the evening of December 11, 1873, viz.—that I should suspend a plate of tourmaline in a vacuum, and see if different amounts of repulsion were produced by allowing light to fall on it after passing through another tourmaline, which could be rotated so as to alter the plane of polarisation of the incident light.

Three separate sets of experiments were tried. The results are the same in each, and as they have been obtained under different circumstances, and are interesting from a theoretical point of view, I will briefly describe each apparatus.

Fig. 5.



The apparatus first used consists of an ordinary torsion apparatus in an inverted T tube, as shown at fig. 5, *a*, *b*, *e*, *f*, made of glass tubing cemented together at *e*, and ground flat at the end *a*. In the centre is blown a circular hole *c*, and another hole, *c'*, is at the end; the edges of these holes are also ground quite flat. *a*, *c*, and *c'* are sealed up by cementing plates of glass *a*, *d*, *d'*, on them. *g* is the connexion to the mercury-pump. The beam *h i* is of glass drawn from square glass tube; *j k* is the glass torsion fibre; *k* is a silvered glass mirror. The plate of tourmaline is attached to the beam at *i*, and a glass counterpoise is fixed at *h* to balance the tourmaline.

In the first experiments a plate cut from a crystal of tourmaline was used at *i*, but it was found that it became so electrical when a ray of light fell on it in the vacuum

that no observations of any value could be taken, the crystal being attracted to one side or the other of the glass tube. A thin plate of artificial tourmaline (herapathite or iodo-sulphate of quinine) was then used at i, instead of the tourmaline, and with this no inconvenience was observed from electrification.

A few experiments showed me that the red and heating rays of the spectrum were most active in repelling this artificial tourmaline, so a platinum spiral, heated to full redness by a 2-cell Grove's battery, was used as the source of radiation.* A large silvered reflecting mirror was placed behind the hot spiral and a lens in front of it, so as to form a highly luminous image of the spiral on the tourmaline. Close to the window c' a large slice of real tourmaline† was mounted as a polariser in a frame, so that it could be easily rotated. The apparatus was covered with black velvet, and care was taken to allow no light to get to the artificial tourmaline except what had passed through the polarising tourmaline.

A luminous index, reflected from the mirror k to a graduated scale, showed the movement of the beam. The contact key was pressed down, and the spiral heated for time sufficient to allow the index to get to the extremity of the first oscillation. The number of degrees on the scale at which the index stopped was noted. Observations were sometimes taken with the tourmalines crossed and parallel alternately, and at other times a series of observations was taken with the polarising tourmaline one way, and then a series with the tourmaline turned the other way. The means of each set of observations, which were fairly concordant, are given below :—

	Artificial and natural tourmalines.	
	Parallel.	Crossed.
	°	°
Group 1	18·0	17·8
„ 2	11·5	13·5
Mean . .	14·75	15·65

Observations were now taken by keeping the battery key down for exactly five seconds :—

	Artificial and natural tourmalines.	
	Parallel.	Crossed.
	°	°
Group 3	3·5	3·5
„ 4	3·4	3·5
„ 5	3·5	3·5
Mean . .	3·47	3·50

These results look as if there were no difference between the actions; but the

* A platinum ball, heated to redness by a gas flame, was at first tried, but the heat from the gas was too great.

† I am indebted to Professor Maskelyne for the loan of several plates of tourmaline of very large size.

apparatus was not very sensitive, and with so small an amplitude as 3·5° much accuracy could not be expected. It was therefore put aside, and the experiments were not resumed for nearly four years.

Apparatus No. 2 is the same in construction as No. 1 (fig. 5), made, however, more delicately, suspended by a finer torsion fibre, and sealed on to a pump with which I can easily bring the exhaustion to the most sensitive point. Instead of a hot platinum spiral, a standard candle is used. The polariser is the same large plate of real tourmaline used in the previous apparatus. With this, a large series of observations were made; the means are given below, arranged in groups :—

	Artificial and natural tourmalines.	
	Parallel.	Crossed.
	°	°
Group 1	24·8	25·2
„ 2	13·5	19·0
„ 3	14·0	16·0
„ 4	18·5	18·5
„ 5	17·0	21·5
„ 6	18·0	18·0
„ 7	16·0	16·0
„ 8	16·0	18·0
„ 9	17·0	17·0
Mean . .	17·2	18·8

260. So far the results show a very slight difference in favour of the crossed tourmalines. The artificial tourmaline being very small, and exposing some bare glass round its edge, it was removed from the apparatus, and a thin slice from a natural crystal of tourmaline was suspended in its place. To avoid the inconvenience of electrification, I adopted a device suggested by Mr. C. F. VARLEY, which answered perfectly—viz., binding the crystal very loosely with the finest platinum wire, so as to form a gridiron-shaped grating about half a millimetre from its surface, the wires being about a millimetre apart. As polariser, a large Nicol's prism was used, for the loan of which I am indebted to Mr. SPOTTISWOODE.

With this arrangement a large number of observations were taken, with the following results :—

	Nicol's prism and natural tourmaline.	
	Parallel.	Crossed.
	°	°
Group 1	18·0	16·5
„ 2	20·5	16·0
„ 3	20·5	17·
„ 4	21·	17·
„ 5	21·	16·5
„ 6	21·5	17·
Mean . .	20·4	16·7

The difference in this case is on the other side. It would now seem that there was more repulsion when the polarised ray passed through the crystal. There was, however, great difficulty in bringing the beam and index ray of light back to zero; the platinum grating was successful in preventing the tourmaline from flying to one or other side of the glass tube and there sticking, but there seemed to be a residual action which kept the suspending fibre in a state of torsion and interfered with the free movement of the crystal.

Another apparatus was therefore made, introducing every refinement which experience suggested, and employing a still finer torsion fibre. A minute portion of a magnetised sewing needle was attached to the beam at the centre, so as to allow the beam each time to be brought to zero by a control magnet outside. The natural tourmaline was discarded, and a large and very perfect crystal of artificial tourmaline suspended in its place. The standard candle was kept two inches from the polarising tourmaline, and sheets of glass enclosing an air space between, and a water cell 5 millims. thick, were interposed to cut off radiant heat. The apparatus was well packed with cotton wool, except in the actual paths of the light.

The means of several observations are collected below into groups. The apparatus was allowed to come to perfect rest between each observation, and the lighted candle was only brought near it just before the screen was removed to take each observation.

	Artificial and natural tourmalines.	
	Parallel.	Crossed.
Group 1	15°	15·5
„ 2	16·5	15·
„ 3	15·5	16·5
„ 4	16·5	16·
„ 5	15·	15·5
„ 6	15·5	15·5
„ 7	16·	16·5
„ 8	16·	16·5
„ 9	15·5	..
Mean	15·7	15·9

Here the difference has vanished to within the limits of accuracy of which the apparatus is capable.

261. Finally, the control magnet was removed further off so as to get greater amplitude of swing. The sensitiveness of the apparatus was thereby considerably increased.

The following are the means of three groups of observations taken with it so arranged :—

	Artificial and natural tourmalines.	
	Parallel.	Crossed.
	°	°
Group 1	40·	46·
„ 2	38·	36.
„ 3	36·	30·
Mean . .	38·	37·3

Here the difference is in favour of the parallel tourmalines, but it is so slight that, like the former result, I do not consider it as the expression of a natural law.

262. The idea when these experiments were first tried was that a slice of tourmaline, being black to a ray of light polarised in one plane, and white to a ray polarised in the other plane, would be repelled when the incident light was quenched by it, and not affected when the incident light passed through it. The idea was a perfectly reasonable one some years ago; but recent researches have proved that the repulsion resulting from radiation is almost entirely a surface action, whilst the action of a tourmaline on a ray of polarised light is one in which thickness is necessary.

The above experiments prove that the special action originally thought possible does not exist in a degree appreciable with the present experimental means.

263. That a polarised ray of light can produce repulsion in a vacuum as well as a ray of common light is proved by the fact that radiometers move readily when exposed to candle light which has passed through Mr. Spottiswoode's large prism. A torsion balance with black pith at one end was also exposed to candle light, two tourmalines being interposed between the candle and the pith. When the tourmalines were crossed there was no repulsion, but when parallel the pith was driven back against the side of the glass tube.

EFFECT OF SHAPE IN INFLUENCING THE AMOUNT AND DIRECTION OF REPULSION.

264. In a preliminary note on the theory of the radiometer, which I had the honour of experimentally illustrating at the meeting of the Royal Society, November 16th, 1876,* I described an experiment in which the vanes of a radiometer were made of gold leaf, lampblacked on one side. The apparatus in which this and most of the succeeding experiments in this division were tried, is the one shown at fig. 4, par. 244. Through the open top, access can readily be obtained, and disks, plates, &c., can be quickly tested by being fixed to the extremities of a pair of aluminium arms with a glass cap in the centre, rotating on the needle point. On submitting the pair of blacked gold leaf disks to experiment in this apparatus, after exhaustion, I found an anomaly in the action. A candle repelled the black surface of one of the disks, but it seemed to repel with almost equal energy the metallic surface of the other disk; one

* Proc. Roy. Soc., No. 175, 1876, vol. xxv. p. 304.

disk moving positively* and the other negatively, according to the one on which the light was allowed to shine. The disk which moved the negative way was somewhat crumpled, and on examining the action more closely I found that the slight curvature of the gold leaf thereby produced was the cause of the anomalous action. By means of screens with small apertures in front of the candle, and by concentrating a small image of the candle flame on various parts of the crumpled disk by means of a lens, motion could be produced in either direction; repulsion being produced when the light fell on a convex, and attraction when it shone on a concave portion of the disk. The gold disk which behaved abnormally happened to be slightly turned up at the edge next the tube, so as to present a bright convex surface to the candle.

265. Experiments were now commenced with a view to clear up this interfering action due to the shape of the vanes. As the experiments are very numerous and only differ from one another in small modifications or details, which have been successively introduced in order to ascertain what are the accidental and what the necessary accompaniments of the phenomena, I will only describe the first in detail, and will give the others of the series as briefly as possible consistent with clearness.

Plates 12 millims. square, cut from thin aluminium foil, were mounted diamond-wise on arms and supported on the needle point inside the bulb shown in fig. 5. The plates were lampblacked on sides facing opposite ways, and the apparatus was well exhausted. The vanes behaved like an ordinary metal radiometer in respect to light

Fig. 6.

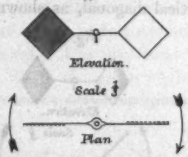


Fig. 7.

and radiant heat. Fig. 6 shows the elevation and plan of the fly, the dotted side representing the one which was lampblacked. The arrows show the direction of positive rotation† when exposed to the light of a standard candle 3·5 inches off. The exhaustion in this and in all cases, except where otherwise specified, was carried to the point at which the fly moved most rapidly to the candle.

266. The outer corners of the aluminium plates were now turned up at an angle of 45°, 4 millims. of the two sides being turned up, leaving 8 millims. flat, as shown in fig. 7. They were lampblacked on the inside, as shown in the figure by dots. A lighted candle, 3·5 inches off, caused very slow and feeble positive rotation. On

* I call the rotation *positive* when the black or driving side is repelled, and *negative* when the side which, under ordinary circumstances, would be the driving side, moves towards the light.

† In the experiments illustrated by figs. 6 to 11 (pars. 265 to 272), the direction of *positive* rotation is shown by the arrows.

shading the light from the black side the bright side was repelled, causing positive rotation, and on shading the light from the bright side the black was repelled, causing negative rotation; but the positive repulsion was rather stronger than the negative repulsion, and consequently when both sides were illuminated the force was only that due to the difference of these repulsions.*

A hot glass shade inverted over the bulb (245, *note*) produced negative rotation, changing to positive on cooling. Both these rotations were stronger than that given by the candle.

267. Instead of 4 millims. of the sides being turned up, 6 millims. were turned up, as shown in fig. 8. The candle gave moderately good positive rotation. On shading

Fig. 8.

the light from the black surface by means of a screen, and letting it shine only on the bright face, there was no movement. On shading the light from the bright side, and letting it shine on the black side, there was apparent *attraction*† with positive rotation, the speed being about half what it was when the light shone on both vanes simultaneously. A hot shade gave negative rotation, that is, in the opposite direction to that caused by light, changing to positive as the vanes cooled.

268. The plates were now folded across the vertical diagonal, as shown in fig. 9.

Fig. 9.

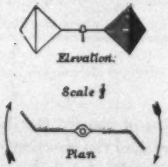
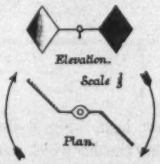


Fig. 10.



The candle gave strong positive rotation in the direction of the arrows. When a screen was interposed so as to allow the light to shine only on the black side, the positive rotation was kept up with scarcely diminished speed, the direction being that of attraction. When the light shone only on the bright surface no rotation took place. A hot glass shade gave good negative rotation, changing to the positive on cooling.

* A radiometer similar to this, but not turned up to quite the same extent, is insensitive to light shining on it in the ordinary way.

† I use the word *attraction* in these cases for convenience of expression. What appears to be attraction is really due to a *vis a tergo*. See par. 312.

269. The above experiment was repeated, the only change being that the plates were folded across their horizontal diagonal, the crease being in a line with the supporting arm. The movements to a candle and a hot shade were the same as in the last experiment (268), but considerably weaker.

270. Flat plates were now used, attached to the arms at an angle of 45°, as shown in fig. 10. They were blacked on the insides, away from the bulb. Exposed to candle light, there was slight repulsion on each face, that on the bright surface being rather the stronger, but not enough to commence rotation. On starting rotation by shaking the bulb, it kept up very slowly in the direction of the arrows. A hot shade gave good rotation in the same direction. There was no reverse movement on cooling.

271. As in the last experiment (270), the plates were mounted at an angle, but they were blacked on the outsides as shown at fig. 11. A candle gave rapid positive

Fig. 11.

rotation. A hot shade gave negative rotation with good reversal of movement on cooling. This form is the most sensitive yet experimented with.

272. Radiometers made of silver flake mica being more sensitive than those made of pith or metal (238), it was deemed of interest to ascertain whether this extra sensitiveness would be retained when the vanes were mounted at an angle, as in the last experiment. This was found to be the case; radiometers constructed with silver flake mica vanes set at an angle, as shown in fig. 11, and blacked on the outside, prove the most sensitive for light hitherto constructed.

SPECIAL EXPERIMENTS WITH SLOPING-VANED RADIOMETERS.

273. From the foregoing experiments it appears that the favourable presentation of the surface of the vanes to the inside of the bulb, has more influence on the movement than has the colour of the surface. A series of experiments was instituted in the hope of clearing up many anomalous results which had attended the application of heat either by hot shades or by hot water to radiometers. The results hitherto obtained had been contradictory, and it was now seen that there might be an antagonistic action between the effect of shape and that of colour of surface, the two actions sometimes acting together and sometimes in opposition.

Five radiometers were made exactly alike in size of bulb, shape of vanes, and degree of exhaustion, and only differing in the material of which the vanes were composed. No. 1 was made of mica, 0·003 inch in thickness.* No. 2 of mica,

* Measured by a Whitworth's measuring machine.

0·0005 inch in thickness.* No. 3 of pith, 0·05 inch in thickness.* No. 4 of aluminium, 0·002 inch in thickness.* These four radiometers were plain on each side, no lampblack being applied. Their appearance is shown in plan in fig. 12. No. 5 was made of aluminium, identical with No. 4, but the vanes were lampblacked

Fig. 12.

on each side instead of being bright. Had the vanes pointed radially, there could have been no tendency for any one of the flies to move either way, but being inclined, the normal movement, on exposure to radiation, should be in the direction of the arrows—a direction which I will call the *positive* direction.

274. The radiometers were tested with a candle. They all moved positively, but with very different rates. With the candle 3 inches off, no movement took place at first; after a little time repulsion was observed, but rotation could not be started. By following up the retreating vane with the candle, rotation was set up, and on then removing the candle 3 inches off, rotation continued in the case of the pith and the two aluminium instruments, but not with the mica. The black aluminium was the easiest to move, then the pith. The bright aluminium fly was more difficult to start than the thick mica fly, but when once set going it moved the quicker of the two. The thin mica fly was the most sluggish of all.

These radiometers are evidently affected much more by the heat from the candle than by the light. I explain the above actions in the following manner.

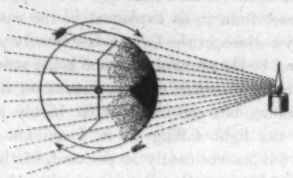
275. I assume that the glass bulb is transparent to the *light* of the candle, but offers considerable obstruction to the ultra-red *heat* rays which accompany the light (246), and that the dark heat rays which are arrested raise the temperature of the glass, which thereupon gives out dark heat. The side of the bulb exposed to the air radiates dark heat outwards, and the inner side of the bulb in contact with the highly rarefied gas, generates molecular pressure, which reacts in all directions (218 postscript), but most powerfully in a direction normal to the surface (312).

276. To explain the action more easily I will first discuss the action of the mica-vaned radiometers exposed to the candle. In fig. 13, the candle is represented shining on the bulb. The rays of light pass through the first wall without action. They then meet the mica, and that also being very transparent, the rays pass through it likewise, and then escape through the opposite side of the bulb, as is shown by

* Measured by a Whitworth's measuring machine.

dotted lines, without absorption and consequently without doing work. But in addition to light, the candle is radiating ultra-red dark heat rays. These in great measure are arrested by the glass, and raise its temperature. The inner surface of the bulb then becomes the surface on which molecular pressure is generated,* as shown

Fig. 13.†



by the shading at the side next the candle. This molecular disturbance presses on the mica vane which is in front of it, and drives it round in the direction of the arrows, as if it were subjected to a bombardment of small shot. The vane, in fact, may be said to be blown round by what may be likened to a wind, which however is not *molar* but *molecular*, inasmuch as there is no wind in the sense of an actual transference of gas from one part of the bulb to the other.

277. One of the flies of the mica radiometer is much thinner than the other (273), and moves less readily to a candle. The reason is this:—

Mica is not perfectly transparent to light and heat; a small portion is arrested, and is converted into heat of temperature. This causes molecular disturbance on the surface of the mica, and thereby assists the motion, as the pressure from the glass and from the mica acts in the same direction. The thick mica naturally obstructs more of the incident rays than does the thin mica, and it also holds more heat. More molecular pressure, therefore, comes from the thick than from the thin mica, and the thick will move better to a candle. A reference to fig. 13 will show why the mica radiometers will not rotate unless the candle is moved round to drive the vane before it. Imagine the fly moving slowly round in the direction of the arrows. When it has moved a few degrees further than is here represented, the advancing vane comes within the layer of pressure, and the retreating vane is emerging from it. Both will therefore be receiving the push, but in opposite directions. The more favourable presentation of the retreating over that of the advancing vane, will not carry the fly round, but it will only cause it to come to rest at such a point that the retreating vane is further from the candle than the advancing vane. If a certain amount of impetus

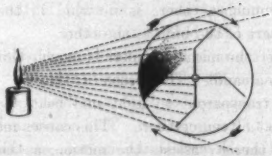
* This may for shortness be called the *driving surface*.

† This fig. and figs. 14, 20, 21, 24, 25, 26, 27, are simply explanatory, and are not to scale. The instrument is shown in plan, but the candle is in elevation and much diminished in size.

were acquired by the fly, if more candles than one were at work, or if sufficient molecular pressure were generated on the face of the mica vanes, there would be no difficulty in getting over the dead centre, and rotation would take place; in default of these conditions the fly soon comes to rest.

278. I will now describe the action of the candle on the aluminium radiometer. When a candle is brought near, the dark heat rays are stopped by the glass, and cause molecular pressure to react from it, as explained in the case of the mica radiometer (276). The luminous rays, which in the former case mostly passed through the vanes and bulb, are now arrested by the aluminium, some being reflected and some absorbed. I have been unable to find an account of experiments on the proportion of incident rays absorbed by aluminium, but considering that highly polished speculum metal absorbs 36 per cent. of the light falling on it, I am not far wrong in estimating that ordinary aluminium foil absorbs nearly 50 per cent. of the incident light. Therefore about half the light falling on the aluminium vanes is absorbed and converted into heat of temperature. Molecular pressure is thus produced on both surfaces of the plate, for the aluminium is so thin, and is so good a conductor of heat, that the two surfaces almost immediately become of the same temperature. In fig. 14 I have

Fig. 14.



endeavoured to represent part of the action which takes place when the candle shines on the aluminium radiometer. The molecular pressure generated on the hot surface of the glass opposite the candle is omitted, as it will be the same as with the mica radiometer shown in fig. 13, and its representation would only complicate the drawing. The light passing through the bulb falls on the aluminium plate, and, raising its temperature, causes pressure to be exerted on all sides. The pressure from the face away from the bulb is mostly dissipated, and may be disregarded, but the molecules rebounding from the face next the glass, cause increased molecular pressure on that side, and produce movement in the direction of the arrows, or positive rotation. As each vane passes the candle it takes up heat, and acquires extra *driving* energy. As it swings round, the opposite side of the glass acts as a *cooler*, and by the time the vane has completed the circle and has radiated away some of its extra heat, it is ready to recommence the cycle of transformation—light, heat, molecular pressure, motion.

Unlike mica, which generates very little pressure on its surface, the aluminium

fly carries sufficient driving power to enable it easily to pass the dead centre opposite the candle. Therefore, as soon as the candle has shone on the aluminium radiometer long enough to warm the vanes a little, rotation readily continues.

279. The action of the pith radiometer is similar to the aluminium. On referring to Table XII., par. 237, it is observed that white pith is repelled with a force of 17·7 by rays which are not cut off by water; that is, by dark heat rays which have escaped the absorbing action of the side of the glass tube in which the experiment was tried. The rays quenched by the pith will reappear as heat, and the slice of pith being of a sensible thickness, and almost a non-conductor, nearly all the molecular pressure will act on the first surface. The action of the candle on the pith radiometer will therefore be similar to that on the aluminium, represented in fig. 14, except that the dissipation of pressure from the back surface of the pith will be almost *nil*. The pith, moreover, being sensitive to the heat rays, and being a non-conductor, may be expected to move quicker than the aluminium, which requires time to get warm throughout. This is found to be the case.

280. The aluminium vanes blacked on both sides, as might be expected, act like the plain aluminium vanes, but in a much stronger degree.

281. The agreement between theory and observation, so far, seemed exact. In the endeavour to clear up the discrepancies I had so frequently met with, I now tried numerous experiments with dark heat applied in various ways to these five radiometers.

282. In par. 245 it is shown that, when I wanted to try the effect of dark heat on a radiometer, I covered it with a hot glass shade, a convenient means of warming the bulb uniformly by heat rays which would not pass through the glass in a radiant form, and thus avoiding the interference of other rays on the material composing the fly. On trying this experiment with the five sloping-vaned radiometers, the results proved very contradictory (273). Generally the effect of the hot shade was to produce negative rotation. Sometimes, however, the movement was positive, and occasionally no rotation at all could be obtained. The vanes would go round once or twice, then quickly stop, and reverse their movement, as if under the influence of two nearly equal opposing forces, sometimes obeying one and sometimes the other. Thinking that the hot shade might have become electrified on handling, I heated it in hot water, and inverted it dripping wet over the radiometers, still with the same contradictory result.

283. To immerse the radiometers in water of about 70° C. appeared a better means of heating the bulbs uniformly on all sides, without producing electrical disturbance. Heated in this manner, the thick mica radiometer moved slowly in the negative direction, and after a short time came to rest.

The radiometer was now removed from the hot water, and allowed to cool. Positive rotation commenced, and after continuing for about a minute it stopped, and then gave one or two turns negatively.

284. The thin mica radiometer behaved differently. When first immersed in hot water, it gave one turn in the negative direction, and then changed to positive, rotating positively for some time at a good speed. It finally came to rest.

When removed from the hot water and allowed to cool, the thin mica radiometer rotated negatively for a considerable time.

285. The bright aluminium radiometer, on immersion in hot water, rotated rapidly in the *negative* direction, and soon came to rest.

When cooling in the air, this radiometer rotated *positively* at a considerable speed.

286. The aluminium radiometer, blacked on both sides, behaved like the plain aluminium one, but in a stronger degree, rotating *negatively* on heating and *positively* on cooling.

287. The pith radiometer, when dipped into hot water, moved in an undecided manner, first a little one way and then a little the other—the tendency, however, being in the *positive* direction.

On cooling, the pith radiometer moved continuously, but slowly, in the *negative* direction, and kept up the movement for a considerable time.

288. The thick mica radiometer was heated over a Bunsen burner till the glass approached its softening point. It was then turned upside down, and allowed to cool till the temperature of the bulb was about 150° C. The cooling having gone on for some time, and taking place entirely by radiation from the outside of the bulb, it was certain that the fly inside was somewhat hotter than the bulb. On now inverting it, so that the fly rested on the needle point, the vanes immediately commenced to rotate in the *positive* direction. When the temperature of the outer bulb was appreciably the same as the room, the vanes stopped, then gave two or three turns the *negative* way, and finally came to rest.

289. Thinking it probable that the kind of dark heat might vary in refrangibility according to its source, and that the rays from hot water, hot glass, and hot metal might affect the materials composing the vanes in a different manner, and being absorbed by one body and transmitted by another might cause the positive or negative rotation, I repeated the experiments, varying the source of heat.

290. The five radiometers were immersed in boiling water; after cooling, they were immersed in water only a few degrees above the temperature of the room. In each case the results were of the same kind as already described with water of 70° C.

291. The five radiometers were covered successively with hot shades of English, French, and German glass, of different thicknesses, and at different degrees of temperature. They were sometimes dry, and at others wet and filled with steam. The results were even more contradictory than with the hot water, and no law could yet be disentangled from the individual results.

292. Heating the bulbs with a gas or spirit flame gave less uniform results than those obtained with the hot shades.

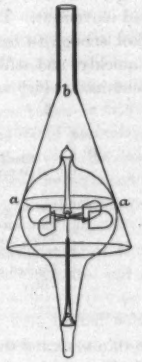
293. A funnel was heated in boiling water, and then allowed to rest on the five

radiometers in succession. They all moved in the *positive* direction, except the bright aluminium radiometer, which remained stationary. When the funnel was removed, the two aluminium and the thick mica radiometers rotated *positively* till they were cold.

294. The funnel was allowed to cool. It was then inverted over a radiometer, and steam was passed through for a second or two. The same experiment was repeated with each radiometer. The results were now equally uniform with those of the last experiment, but the rotation was *negative*; the bright aluminium fly moving the best of all, and the pith fly the least.

295. Order now began to evolve itself from the mass of contradictions I had hitherto encountered. Let fig. 15 represent the funnel covering one of the radiometers: and first let it be supposed that the funnel has been heated in hot water, and then inverted over the bulb. The funnel touches the bulb in a ring at *a a*, in a nearly equatorial position, and therefore this ring of the bulb gets hotter than any other part, as radiant heat from hot glass has much inferior warming power to actual contact with hot glass. Next, imagine the funnel to be cold, and steam passed in for a second or two. The upper portion of the funnel, *a a b*, together with the *north pole* portion (if I may use the expression) of the bulb gets warm, whilst the equator is cold.

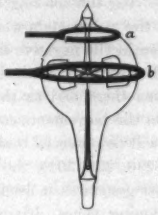
Fig. 15.



296. The rule appears to be that when the equatorial part of the bulb of the radiometer is warmed, positive rotation takes place, and when the polar portion is warmed negative rotation takes place.

297. Further experiments soon showed that this law was likely to be the true one. The radiometers were dipped into hot water one-third of the way up the bulb. Strong *negative* rotation took place in each case.

Fig. 16.



298. A thick brass ring was selected with an internal diameter about half that of the bulb, fig. 16, *a*. It was heated to about 400° C., and then put on the five radiometers in succession at *a*. All moved in the *negative* direction at a tolerably good speed.

On removing the hot ring from the two aluminium radiometers a reversal of movement took place and faint positive rotation was observed. With the thin mica and the pith radiometers no change of direction could be detected on cooling, the negative rotation keeping up for a considerable time.

299. A thick brass ring, a little larger in diameter than the bulbs (*b*, fig. 16), was heated to 400° C., and then held round the centre of the bulb of each radiometer in succession in the position *b*. All the flies revolved in the *positive* direction. The thick mica fly went at a maximum speed of 60 revolutions a minute, the thin mica fly made 36 revolutions a minute, the pith 15 revolutions a minute, the bright aluminium 11 a minute, and the blacked aluminium 1 revolution a minute.

300. When the equatorial hot ring was removed, and the bulbs were allowed to cool, no reversal of movement took place with the thick mica or the two aluminium flies. The thin mica and the pith flies showed decided reversal on cooling.

301. To still further test the question of the change of direction on cooling, the experiments with the two brass rings were again tried on the five radiometers. The rings, this time, were made red hot, and were held in position till the flies were in rapid movement. The rings were removed, and as soon as the hot part of the bulb was cool enough to bear handling, it was dipped into cold water, so as to chill the glass quickly, and still keep the fly warm. Tried in this way very decided results were obtained, which will be better understood in the form of a Table.

Material composing the fly of the radiometer (*favourably presented.*)	Hot ring applied above.		Hot ring applied equatorially.	
	Heating.	Cooling.	Heating.	Cooling.
Thin mica	−	−	+	−
Thick mica	−	?	+	+
Bright aluminium	−	+	+	+
Blacked aluminium	−	+	+	+
Pith	−	−	+	−

The thin mica and the pith when cooling, after being heated above, kept rotating negatively for a long time. The others soon came to rest. The movement of the thick mica on cooling, after being heated above, was contradictory, some experiments giving it + and some −. The other movements were very decided.

Applying the hot ring below had exactly the same effect as applying it above, and when the radiometers were heated above and below, the equator being kept cool, the rotation in the negative direction was very strong and rapid.

302. Having described the various phenomena, I will show how far the theory explains them, and as the radiometers differ in construction and action, I will first discuss the movements common to all.

It will be observed that when heat is applied round an equatorial ring of the bulbs (294, 296, 299, 301), the rotation is always in the *positive* direction. The hot ring of glass generates molecular disturbance, which presses towards the centre and strikes the sloping vanes, driving them round as if a wind were blowing on them (276). In fig. 17 I have tried to represent this action. The positive movement is inde-

pendent of the material of which the fly is made, and is only slightly increased or diminished according to the conducting power of the fly for heat. The lighter the weight of the fly to be driven round the easier it moves, and the heavier the fly the longer it keeps in motion after it is once started.

Fig. 17.

Fig. 18.

303. When heat is applied to either pole of the bulb the action is of a different character, *negative* rotation taking place (295, 296, 298, 301). A moment's consideration will show that the molecular pressure proceeding from a hot pole of the bulb will strike the *inner* surface of the sloping vanes, and driving them before it, will cause a rotation which appears *negative* to an observer, although it is really *positive* to the direction of pressure. It is not easy to represent the lines of force on a flat diagram, but fig. 18 will sufficiently illustrate the mode of action. The heat is supposed to be applied near the centre, and the molecular pressure radiating on all sides presses the vanes chiefly on the inner surfaces.

This action, like the positive rotation when the bulbs are heated equatorially, is in great measure independent of the material of which the vanes are made and of its conducting power for heat.

304. The anomalous results obtained when the radiometers were heated with hot glass shades or hot water (282 to 293), the vanes sometimes rotating one way and sometimes the other, but chiefly in the negative direction, are now completely accounted for. Polar heating gives negative, and equatorial positive rotation, and therefore when both are heated together by immersion in hot water the direction of motion is governed by the stronger of these two forces. A much larger surface of the bulb is effective in producing negative than positive rotation, and therefore the tendency of hot water is to drive the vanes negatively. If, however, the lower part only of the bulb is dipped into hot water (297), strong negative rotation takes place. Owing to accidental conditions, such as the shape of the bulbs, the size of the vanes, and their position in respect to the centre, the two opposing forces may be more or less evenly balanced, and a very little will cause one or the other to preponderate. A hot shade, for instance, if it is very large, may heat the bulb uniformly all over and give negative rotation, whilst if it is tall and narrow, the equator of the bulb receives most heat, and positive rotation ensues.

305. When explaining the action of light from a candle on the radiometers

(276 to 280), I showed that the glass heated by the ultra-red rays became hot, and acted as the driving surface, generating molecular pressure and causing the sloping vanes to turn in the positive direction. I also showed that another action took place at the same time, the vanes got warm and became themselves sources of molecular pressure. Now the amount of molecular pressure thus generated depends on the capacity of the material of the vanes to absorb heat. Thin mica, owing to its thinness, will hold very little; thick mica will hold more; and aluminium, on account of its superior mass and good conducting power, will hold most. This extra capacity for heat causes more molecular pressure to proceed from the aluminium and thick mica than from the thin mica, and generates a proportionate amount of driving power on the surfaces of the vanes, turning them, as shown in paragraph 278 and fig. 14, in the positive direction, and supplementing the action of the equatorial ring of hot glass (302).

306. When these radiometers are heated at the poles they go *negatively*, and when heated at the equator they rotate *positively*. On allowing them to cool, the flies being inside must lag behind the glass bulb in losing heat, the vanes will therefore be hotter than the outer bulb; two forces are now at work tending to move the flies in opposite directions. These forces are—

(*a*.) The increased temperatures of the vanes and consequent generation of molecular pressure from their surfaces. That from the inner surface need not be taken into account, but that from the outer surface produces pressure between it and the glass bulb, and tends to produce positive rotation.

(*b*.) The radiation of heat from the inner fixed parts of the radiometer, such as the supporting stem, the needle, the upper glass tube, &c. This causes a stream of molecular pressure to strike against the inner surfaces of the vanes, and gives them a tendency to negative rotation.

307. Of these two forces, the latter (*b*), will be practically constant in intensity, whatever be the material constituting the vanes. The former force (*a*) will, however, vary considerably, being very slight in thin mica and pith, and strong in aluminium. With thin mica and pith, therefore, force *b* will preponderate, and the fly will rotate negatively; whilst with aluminium the force *a* will preponderate, and the fly will rotate positively.

308. As the thickness of the mica increases, force *a* will gain strength, and the phenomena exhibited by the thick mica radiometer will be produced, namely, tendency to rotation in an undecided manner, first one way and then the other, according as one force or the other gains temporary ascendancy.

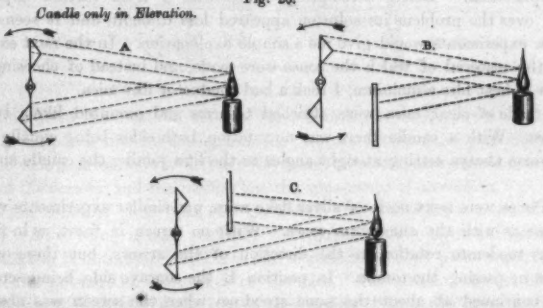
In fig. 19, A and B, I have attempted to represent an aluminium and a mica radiometer, cooling from a high temperature, the aluminium fly, under the preponderating influence of force *a*, going positively, and the mica fly under the preponderating influence of force *b*, going negatively.

Fig. 19.

ACTION OF RADIATION ON CONES, CYLINDERS, AND CUP-SHAPED VANES.

309. Having investigated the simplest form of favourably-presented vanes, I turned my attention to more complex shapes, hoping thereby to obtain verifications of the laws which have been described in the previous pages. A pair of thin aluminium disks, cut half across the diameter, were bent into cones and mounted on two arms as a radiometer, the cones facing opposite ways. Preliminary experiments having shown that an effect of attraction, already noticed at pars. 267 and 268, was strongly marked with these cones, the following experiments were also tried. A standard candle was placed with the centre of its flame 3 inches from the centre of rotation of the arm carrying the cones. The exhaustion having been brought to about 20 millionths of an atmosphere, the revolutions under the influence of the lighted candle were timed. With no screen in front, as in fig. 20, A, the arms made 21·8 revolutions a minute in the positive direction,—the mean of eight closely concordant observations.

Fig. 20.



A screen was then interposed between the candle and the concave cone, as in fig. 20, B, so that the radiation should only fall on the convex surfaces of the cones, as they emerged successively out of the shadow of the screen. The rotation became

slower, and when the speed was uniform, on timing the revolutions I found the mean of seven observations to be 11 revolutions a minute in the positive direction.

The screen was now placed as in fig. 20, C, so as to cut off the light from the retreating cones, and allow it to fall only on the concave cones as they were approaching the light. A very slight diminution in velocity took place, but the rotation continued in the same direction as in the two previous instances. The speed was 9·6 revolutions a minute. Finally the candle was blown out, and when the cones were still, and the bulb cold, the candle was again lighted, the arrangement remaining as at C. Rotation immediately commenced, the hollow cone advancing towards the light, and the speed rapidly increasing till it became uniform at 9·5 revolutions a minute.

These results show that the speed of rotation produced when the candle shines on the advancing and retreating cones simultaneously, is practically made up of the sum of the speeds attained when the radiation is allowed to fall on either side of the cones separately. Adding the speed in position B (11 revolutions a minute) to the speed in position C (9·6 revolutions a minute), will give 20·6 revolutions a minute: a speed which, allowing for the imperfection of the candle, is sufficiently near that actually observed—namely, 21·8 revolutions a minute.

The candle was brought nearer, and the experiments repeated. The velocities were:—

In position A, 49·2 revolutions a minute.
" B, 25·2 " "
" C, 26·7 " "

310. The apparent attraction observed in position C, at first offered some difficulty in its explanation. Before attempting to theorise I tried further experiments. Thinking over the problem its solution appeared less difficult, and it seemed likely that a few experiments would give me a simple explanation. In the next experiment I varied the material of which the cones were made, and instead of choosing a good conductor of heat like aluminium, I took a bad conductor like mica.

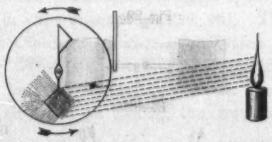
Cones made of clear mica were attached to arms and mounted like a two-vaned radiometer. With a candle there was no rotation, both sides being equally repelled, and the arm always setting at right angles to the line joining the candle and axis of rotation.

311. Cones were next made of silver flake mica, and similar experiments were tried with these as with the aluminium cones. With no screen in front, as in fig. 20, A, there was moderate rotation in the direction of the arrows, but there was great hesitation in passing the candle. In position B, the concave side being screened off, rotation continued at about the same speed as when the screen was absent, or if anything a little faster. In position C, the convex side screened from the light, there was no movement.

312. The explanation of the apparent attraction is now clear. The effect of bend-

ing the plates, or of making cones of them, is to produce a more favourable presentation to the inner surface of the glass bulb. Radiation falls from the candle on the aluminium; some is reflected and is lost, but a portion is absorbed to be converted into thermometric heat or heat of temperature (171, 195, 278). Aluminium being a good conductor of heat, and the thickness of metal being insignificant, it becomes equally warm throughout, and a layer of molecular disturbance is formed on each surface of the metal. At a low exhaustion the thickness of this layer is not sufficient to reach from the metal cone to the side of the glass bulb; as the exhaustion increases, this layer extends further from the generating surface, until at a sufficiently high exhaustion the space between the side of the glass bulb and the adjacent portion of the metallic cone is bridged over, and pressure is exerted between the two surfaces. A reference to the diagram (fig. 21) shows how this pressure will act. The direction of pressure is indicated by dotted lines issuing from the metal cone; it is assumed that the exhaustion is such as to allow the layer of molecular disturbance under the influence of the candle to extend for 5 millims. from the surface of the metal, and I have considered that the pressure acts in a direction normal to the surface (really it will act in all directions, but for the sake of illustration I confine myself to the direction in which it acts with greatest force). The rays from the candle fall on the concave surface of the cone; the substance being a good conductor of heat, molecular pressure is induced in the direction and to the distance shown by the dotted lines (fig. 21), the pressure being greater the nearer the layer is to the metal.

Fig. 21.



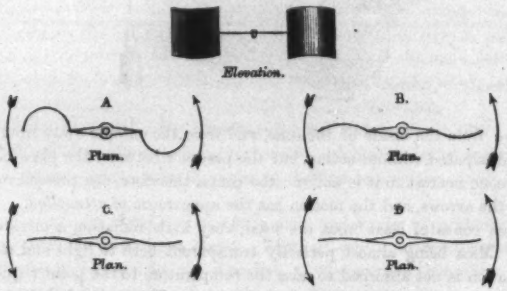
The pressure from the inside of the cone, and from the outside away from the side of the glass, is dissipated without acting, but the pressure between the glass bulb and the side of the cone nearest to it is active; the cones, therefore, are pressed round in the direction of the arrows, and the motion has the appearance of *attraction*.

§13. When cones of clear mica are used, very little radiation is arrested by them (276, 277). Mica being almost perfectly transparent both to light and radiant heat, enough radiation is not absorbed to raise the temperature to the point required to produce molecular pressure on the surface of the mica. The cause of the set of the two cones equi-distant from the candle is that the portion of the bulb nearest the candle gets warm, and this warm piece of glass does not act by radiation but is itself the repelling surface, through the intervention of the molecules rebounding from it with a greater velocity than that with which they strike it (219).

When silver-flake mica is used to make the cones, the action is different. Here some of the light and heat are arrested, with a consequent rise of temperature. But silver-flake mica being a very bad conductor of heat, most of the molecular pressure is exerted from the surface on which the light falls, and very little is generated on the other side. In position C, fig. 20, when the light shines only on the concave surface no motion is produced, as no pressure is generated on the surface away from the light; whilst in positions A and B, where the light shines on the concave surface, the movement is nearly equal in velocity. No effect being produced by the light shining on the concave surface, no retardation is caused when the light is screened from it.

314. The influence which a variation of shape of the moving fly has on the direction and amount of its repulsion depends on favourable presentation to the surrounding bulb. A very little alteration in angle of presentation has more effect than a great difference of colour. It remains to be seen, however, what angle or inclination of the vanes to the glass bulb is the most favourable. Cones being inconvenient in shape, I employed portions of cylinders wherewith to shape the vanes. Four sets of cylindrical aluminium vanes were mounted on arms, and pivoted on needle-points, in four bulbs. They were made at the same time and were alike in all respects, except in the radii of curvature of the cylinders on which the vanes were curved. The vanes were of thin aluminium, and the bulbs were exhausted simultaneously by being sealed on to four arms of a five-tube mercury pump, so as to ensure the exhaustion being identical in the four bulbs. Fig. 22, A, B, C, D, shows the four sets of vanes drawn

Fig. 22.



the full size. The radius of curvature of A is 5 millims., of B 10 millims., of C 20 millims., and of D 30 millims. Each vane is 10 millims. high and 10 millims. across the chord of the arc; consequently there is more metal in the vanes of deeper than in those of shallower curvature. This was thought to afford a fairer means of

comparison than if the same area of metal had been present in each vane, for in that case each alteration of curvature would have altered the distance between the glass and the edge of the vane.

315. These four radiometers were exhausted and tested with a standard candle 3 inches from the centre of rotation. As the exhaustion approached the point of greatest sensitiveness, the fly A was the first to move, and it was in good rotation in the direction of the arrows before the others would rotate at all; soon after A and B were rotating, C commenced to rotate, but it required the exhaustion to be carried to a higher point before I could get rotation in D.

At the exhaustion corresponding to maximum sensitiveness, the rates of rotation were as follows:—

A made	21·4	revolutions	a	minute.
B „	15·0	„	„	
C „	10·3	„	„	
D „	4·6	„	„	

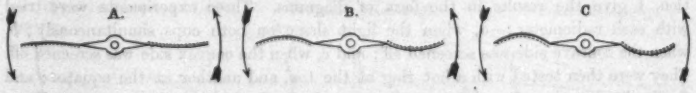
These figures show that the deeper the curvature, up to half a circle, the greater the repulsion.

316. The action of dark heat was now tried, as in the experiments with the radiometers, with "favourably presented" flat vanes. Dipped into hot water they behaved like the aluminium instruments (285, 286), rotating *negatively* whilst getting hot, then coming to rest, and rotating *positively* on cooling.

317. Experiments were now tried with hot rings applied at the poles and at the equator of the bulbs, as in experiments 298, 299, 301. The results fully confirmed those then obtained, and afford an additional proof that the explanation given in pars. 302, 303 is correct. When the hot ring was applied above, *negative* rotation took place, and when the heat was applied only to the equator of the bulb, *positive* rotation took place. In all cases, on cooling, the movement was in the positive direction.

318. The shape of the vanes was now again altered. It was found that cups were more easily affected by radiation than portions of cylinders, and that they were also more

Fig. 23.



easily fashioned into shape. Spherical moulds were prepared with radii of curvature respectively of 35, 14, and 10 millims. By means of these moulds, disks of gold foil, 14·5 millims. diameter, were bent in the form of shallow cups, brightly polished on both sides. They were mounted in pairs in the experimental bulb, fig. 4 (244), and

blacked on the concave surfaces, as shown in fig. 23, A, B, and C. On exposure to the standard candle, 3 inches off, the shallowest cups, A, rotated with a speed of 16·6 revolutions a minute, the intermediate cups, B, made 54 revolutions a minute, and the deepest cups, C, made 60 revolutions a minute.

These experiments corroborate those tried with the aluminium cylinders (313), and prove conclusively that the deeper the curvature the stronger the repulsion.

319. It will be observed that the cups are blacked on the concave side, and bright on the other. Had the vanes been flat disks, the candle would have strongly repelled the black side. The very slight curvature of the shallowest disks, A, is, however, sufficient to overcome the repelling action of radiation on the black surface, and to leave a considerable balance in favour of the polished side.

It now became of interest to know what would be the effect of light on cups blacked on different sides. The following experiments were therefore tried with the pair of gold cups of intermediate curvature, B, fig. 23, and also, for the sake of comparison, on similar pairs of thin aluminium cups. For convenience of comparison I put the results in a tabular form.

	Standard candle 3 inches off.		Hot shade.	Cooling.
	Speed of rotation.	Direction of rotation.	Direction of rotation.	Direction of rotation.
Gold Cups.				
Both sides bright	18 revs. a minute	⟶ (	⟵ (	⟶ (
Concave blacked	54 ,, ,,	⟶ (	⟵ (	⟶ (
Convex blacked	60 ,, ,,	⟶ (	⟵ (	⟶ (
Both sides blacked	67 ,, ,,	⟶ (	⟵ (	⟶ (
Aluminium Cups.				
Both sides bright	26 ,, ,,	⟶ (	⟵ (	⟶ (
Concave blacked	54 ,, ,,	⟶ (	⟵ (	⟶ (
Convex blacked	75 ,, ,,	⟶ (	⟵ (	⟶ (
Both sides blacked	86 ,, ,,	⟶ (	⟵ (	⟶ (

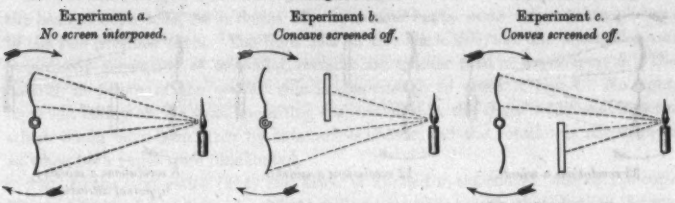
320. These four sets of aluminium cups were permanently mounted in bulbs, and were exhausted together as described at par. 314. They were sealed off at the point of maximum sensitiveness, and tested with a standard candle 3·5 inches off, the whole being enclosed in a space lined with black velvet. To avoid lengthened description, I give the results in the form of diagrams. Three experiments were tried with each radiometer:—*a*, when the light shone on both cups simultaneously; *b*, when the concave side was screened off; and *c*, when the convex side was screened off. They were then tested with a hot ring at the top, and another at the equator; and finally the direction of motion on cooling was observed.

321. To save repetition, I will here state that in all four cases, the hot ring applied to the upper part of the bulb gave *negative* rotation, and equatorially applied gave *positive* rotation. The direction of movement during cooling was in each case *positive* (301). With the cups blacked on both sides, the revolutions, both

under the influence of heat and during cooling, came rapidly to a maximum, and then soon stopped.

322. Series I.—Aluminium Cups, bright on both sides.

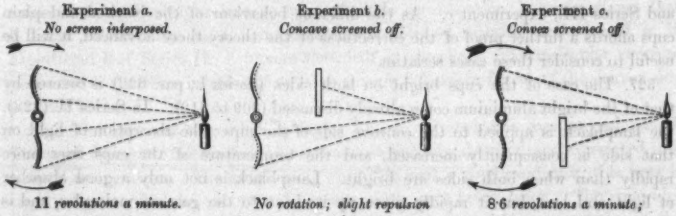
Fig. 24.



18 *revolutions a minute.* | 8 *revolutions a minute.* | 8·6 *revolutions a minute; apparent attraction.*

323. Series II.—Aluminium Cups, blacked on the concave side.

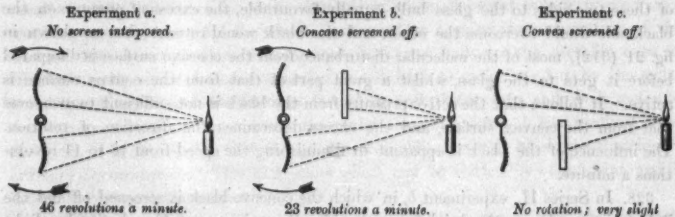
Fig. 25.



11 *revolutions a minute.* | *No rotation; slight repulsion only.* | 8·6 *revolutions a minute; apparent attraction.*

324. Series III.—Aluminium Cups, blacked on the convex side.

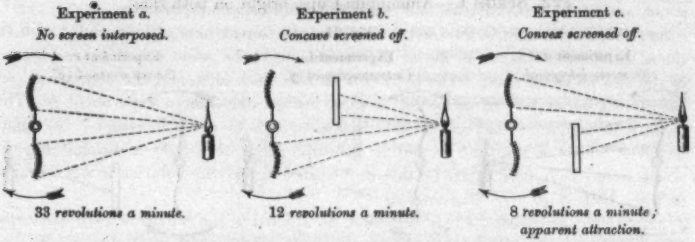
Fig. 26.



46 *revolutions a minute.* | 23 *revolutions a minute.* | *No rotation; very slight repulsion.*

325. Series IV.—Aluminium Cups, blacked on both sides.

Fig. 27.



326. It will be observed that in Series I., experiment *c*, Series II., experiment *c*, and Series IV., experiment *c*, I get the same apparent attraction as with the bright aluminium cones (309, 310). The explanation given in par. 312 covers all these cases, and also accounts for the absence of rotation in Series II., experiment *b*, and Series III., experiment *c*. As the different behaviour of the blacked and plain cups affords a further proof of the correctness of the theory there advanced, it will be useful to consider these cases seriatim.

327. The case of the cups bright on both sides (Series I., par. 322) is covered by that of the bright aluminium cones already discussed (309 to 312). In Series II. (323), the lampblack is applied to the concave side of the cups; the absorption of light on that side is consequently increased, and the temperature of the cups rises more rapidly than when both sides are bright. Lampblack is not only a good absorber of light and heat, but it rapidly gives up its heat to the gaseous molecules, and is thereby a most powerful generator of molecular pressure, whilst the bright side, giving up heat less easily, produces less molecular pressure. An excess of molecular pressure is therefore generated on the concave side by virtue of its black surface, and a less amount of pressure produced on the bright convex side. Were the presentation of these two sides to the glass bulb equally favourable, the excess of pressure on the black side would overcome the other, and the black would retreat; but as shown in fig. 21 (312), most of the molecular disturbance from the concave surface is dissipated before it gets to the glass, whilst a great part of that from the convex surface is active. It follows that the active pressure from the black is not sufficient to overcome that from the convex surface, and the excess determines the direction of rotation. The influence of the black is apparent in diminishing the speed from 18 to 11 revolutions a minute.

328. In Series II., experiment *b*, in which the concave black is screened off and the light shines only on the bright convex side, there is no rotation but only slight

repulsion. The light falls on a polished metallic surface, and about half is reflected without absorption (278). That which is absorbed acts as in the last case, but the forces on each side being more nearly equal, the balance in favour of the convex side is not enough to cause rotation and can only produce slight repulsion.

329. When the light is screened from the bright convex side and allowed to fall on the black concave side, as in Series II., experiment *c*, the same action takes place as in the two previous cases. The light falls on the black side, and the absorption and consequent generation of molecular pressure are greater than in experiment *b*. The balance in favour of the convex side is now enough to drive it round. No light, however, falling on the vane presenting the convex side, the slight additional impetus which would have been given by this vane is absent, and the rotation is not so rapid as when both vanes were illuminated.

330. In the next series (324) the black is applied to the convex side of the cups. The pressure arising from the black surface, conspiring with that due to favourable presentation, drives the fly round with a greater speed than in any of the other experiments—viz., at a rate of 46 revolutions a minute. It is easy to understand that cutting off the light from the convex cup, as in experiment *b*, will diminish the speed, but it is not immediately apparent why the rotation stops when the light is screened from the bright concave cup. A little consideration, however, shows that it must be so. The light here shines on a polished metallic surface, and as in experiment *b* of Series II., not more than half is absorbed. The molecular pressure generated is therefore insufficient to leave enough balance in favour of the convex side to drive it round.

331. The apparent attraction in Series IV., experiment *c*, is easy to understand. The light falling on the black surface is almost entirely absorbed and converted into heat of temperature. The metal being very thin and a good conductor, this heat is equally apparent on the convex and concave sides, both being black. The molecular pressure on each face is therefore equal, and the more favourable presentation of the convex side determines the excess of active pressure in its favour.

332. In testing the action of dark heat on these metallic radiometers by immersing them in hot water, I noticed that the negative rotation which generally resulted (304) took much longer to sink to rest when all bright cups were used than would appear necessary for the whole instrument to acquire the temperature of the water. The communication of heat from the glass bulb to the metallic cups is effected not by conduction or convection (in addition to radiation), but by the molecules travelling to and fro between the glass and the metal; and each molecule depositing or handing on towards the metal the extra force it has received from the glass, it is conceivable that the process of equalisation may be slower than under ordinary circumstances. This is a point which can be settled by experiment, and I intend to return to the subject.

333. When a radiometer immersed in hot water has come to rest, the approach

of a lighted candle causes rotation in the positive direction. But the action is not so strong as when the radiometer is cold or no water intervenes.

334. A four-armed cup-shaped aluminium radiometer, the cups being 10 millims. in diameter and the radius of curvature being 6 millims., was sealed on to the mercury pump. During exhaustion accurate observations were taken of the number of revolutions per minute caused by one or more standard candles 3 inches from the centre of the bulb. At the same time observations of pressure were taken and the exhaustion was carried to a very high point. The results are shown in the following Table:—

Pressure in millionths of an atmosphere.	Number of candles used.	Number of revolutions per minute.	
		Revolutions.	Reduced to 1 candle.
577·0	1	1·0	1·0
400·0	1	3·1	3·1
309·0	1	4·8	4·8
219·0	1	7·0	7·0
159·0	1	10·0	10·0
102·0	1	16·6	16·6
69·0	1	22·2	22·2
41·5	1	26·8	26·8
27·8	1	25·6	25·6
24·0	1	25·0	25·0
19·5	1	23·8	23·8
14·7	1	21·4	21·4
9·5	1	16·4	16·4
8·6	1	15·0	15·0
6·5	1	12·5	12·5
3·8	1	7·1	7·1
2·5	2	9·4	4·7
1·5	3	6·6	2·2
0·9	4	8·0	2·0
0·23	5	4·5	0·9
0·2	5	0·0	0·0 stopped.

The first column gives the millionths of an atmosphere* at which the experiment was tried. The second column gives the number of candles, 3 inches off, used to produce rotation. Up to 3·8 millionths of an atmosphere one candle was sufficient, beyond that rarefaction a greater number was required. At 0·2 millionth five candles ceased to cause rotation. The third column gives the actual number of revolutions obtained with one or more candles, each recorded observation being the mean of several. The last column gives the revolutions per minute, calculated from the third column on the assumption that the number of revolutions per minute is in

* 0·2 millionth = 0·00015 millim.
1·0 millionth = 0·00076 „
4·0 millionths = 0·00304 „
577·0 millionths = 0·43825 „
One atmosphere = 760·00000 „

direct proportion to the number of candles (149). This law is somewhat interfered with at close quarters by the heating of the bulb and fly when extra candles are brought near; but for such an experiment, in which great accuracy cannot be expected, and which is only of illustrative interest, the figures given are near enough.

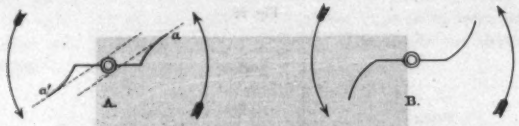
Fig. 28 shows the curve plotted from these observations, using the first and fourth

Fig. 28.

columns, and omitting the observations at 577 and 400 millionths of an atmosphere, so as not unduly to extend the diagram. The curve traced through the dots representing observations, illustrates the gradual increase of sensitiveness up to a certain point of rarefaction, and the sudden drop after that point is reached.

335. To further test the theory that the direction of rotation of the curved vanes depends not on any special effect of curvature as such but on favourable presentation, Professor STOKES suggested that I should make a radiometer having the curved vanes sloping, as shown in fig. 29, A, so that the tangent at the extremity a would

Fig. 29.



fall below the centre, and the same at a', or at most pass through the centre. Such a fly ought to move in the direction of the arrows, or in the same direction as a fly made like B (fig. 29), under the same circumstances, although the curvatures lie in opposite directions.

On trying the experiment with the fly A, I found that when exhausted to the most sensitive point a candle repelled each face with nearly equal force, and therefore no rotation took place, although the tendency was in the direction of the arrows. When heated with a hot ring round the equator of the bulb, strong rotation took place in the direction of the arrows; there was no reverse movement on cooling.

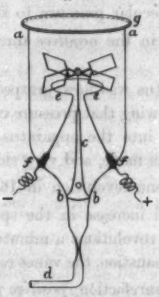
A radiometer fitted with a fly like B revolved very well in the direction of the arrows.

EXPERIMENTS WITH DARK AND LUMINOUS HEAT APPLIED INTERNALLY.

336. The experiments on the action of dark heat on radiometers with "favourably presented" vanes, tried with hot rings applied above, equatorially, and below (298, 299, 301), could not give results of very great accuracy, as radiation heated a considerable portion of the bulb on each side of the hot ring. In some of the observations the results scarcely accorded with theory, and although I could explain most of the anomalies, there were irregularities which seemed to point to another influence which might cause me to modify the theory of the action of dark heat on the vanes. For strict investigation of this it was necessary to contrive a very intense source of heat always ready to be applied in the same place; the heat should not pass through glass, and it should be completely under control as to intensity and time of action. The vanes also should be turned in the most favourable position for rotating under the influence of the molecular pressure, and the apparatus should be capable of having the exhaustion carried to a very high point and measured when an observation was taken. These advantages are all secured in an apparatus represented in fig. 30.

This apparatus consists of a wide glass tube, *a a*, *b b*, drawn off narrow at the end *b b*, and a stem, *c*, sealed in to hold a needle point. To the narrow end a fine tube, *d*, is attached to connect the apparatus to the mercury pump. Round the needle is placed a ring of fine platinum wire, *e e*, the ends of which are joined to thicker

Fig. 30.



platinum wires passing through the glass at *f f*. A current of electricity from two Grove's cells, turned on or off by a contact key, gives the power of making the wire ring, *e e*, red hot when desired. The top of the wide tube is ground and polished quite flat, and is covered by a piece of plate glass, *g*, which can be cemented on so as to form a perfectly tight joint, and may be removed by warming so as to admit of any experimental fly being supported on the needle point.

The fly used in these experiments consists of four square vanes of thin clear mica, supported on light aluminium arms, and having in the centre a small glass cap, which rests on the needle point. The vanes are inclined at an angle of 45° to the horizontal plane. They are in such a position that when rotating the centres of the vanes pass along the platinum ring and keep about 5 millims. distant from it.

337. In describing the direction of rotation of this fly, I shall consider the observer's eye to be on a level with the plane in which the fly rotates, and the direction recorded will be that taken by each vane as it passes in front. Assuming that the fly shown in fig. 30 is rotating in the same direction as the hands of a watch, were the watch laid face upwards on the top of the plate glass cover, each vane will be fore-shortened, and passing the observer will have the appearance of /. The direction of rotation in this case will be expressed by ∠, and will be considered as *positive* rotation —*i.e.*, as the direction which would be followed by the fly were molecular pressure to proceed from the platinum wire.

338. The apparatus was exhausted till the gauge showed a pressure of 8 millionths of an atmosphere. Contact was made with the battery, the platinum ring became hot,

and the vanes rotated rapidly in the *positive* direction, ◿ as if driven round by molecular pressure coming from the hot wire. The rotation kept up with great rapidity as long as the wire was kept hot, and did not show any signs of diminution of speed.

When the apparatus was again cold, and the vanes quiet, I put a finger on the top plate of glass so as to cause molecular pressure to strike the vanes from above downwards. The vanes now moved in the *negative* direction, ◺ or normally to the source of pressure.

The lower part of the apparatus was now grasped in the hand to warm it, when positive rotation commenced, showing that pressure came from beneath.

339. Air was now admitted into the apparatus until the gauge was depressed 12 millims. Battery contact was made, and very slow *negative* rotation immediately took place, ◺ at the rate of one revolution in 168 seconds. The exhaustion was continued, followed by a gradual increase in the speed up to about 400 millionths, at which point the rate was 10 revolutions a minute, still in the negative direction. A little beyond this degree of exhaustion, the vanes refused to move when the platinum wire was heated. At a higher rarefaction, *positive* rotation, ◿ took place. At a rarefaction of 34 millionths of an atmosphere (about the point of maximum sensitiveness for a radiometer), the speed of the vanes was 200 revolutions a minute. At 3 millionths of an atmosphere the speed was 300 revolutions a minute; and at 1 millionth of an atmosphere the speed continued about the same. Owing to the cement joint I was unable to get a greater amount of rarefaction with this apparatus.

340. These results are of interest in many respects. When using a candle as the source of radiation, I have always found very little repulsion until the gauge has risen to within about 5 millims. of a vacuum; from this point the repulsion increases steadily up to a rarefaction of about 35 millionths of an atmosphere, when it rapidly sinks, until at 0·1 millionth it is less than one-tenth of its maximum.* Below 5 millims. attraction or repulsion takes place according to circumstances which are not clearly explained; but above that point, when repulsion has fairly commenced, I have never observed a change of sign. In the experiments just described, the radiation from an ignited platinum wire is used; there are only about 5 millims. space between the wire and the fly, and no glass intervenes. The results, therefore, are likely to be much more definite than with the usual radiometer-kind of apparatus, and the actions should commence at a lower pressure.

341. In previous experiments with candles, the abnormal movement at low exhaustions was faint and irregular; here they occur with a sharpness which gives one hope of getting at a law. The *negative* rotation of the fly is evidently the analogue of the *attraction* observed in my early experiments at low exhaustions, both being abnormal

* Proc. Roy. Soc., Nov. 16, 1876, No. 175, p. 305.

on the supposition that the movement is due to a push away from the source of radiation.

In an experiment tried in 1875* I used a pendulum with a magnesium weight at the end (99), exposed in vacuo to the radiation from a platinum coil ignited by electricity. The distance from the pendulum bob and the spiral was 7 millims., and two series of observations were given in tabular form (100), showing the direction and amplitude of the swing of the pendulum at different barometric heights when the wire was ignited. The hot wire gave *attraction* in air of ordinary density; this kept pretty constant up to a pressure of about 20 millims., when the attraction began to increase. At about 1 millim. the attraction was at its maximum. Above this exhaustion the attraction suddenly dropped and changed to repulsion, which kept on increasing up to the highest exhaustion I was then able to get.†

In the present experiments the parallel is sufficiently close to show that the same causes are at work. Negative rotation is apparent 12 millims. below a vacuum, and a negative movement would be detected at much lower exhaustions. This negative movement rises to a maximum, suddenly sinks to zero as the exhaustion proceeds, and gives place to a positive rotation which keeps up at nearly a maximum speed and at an exhaustion which would almost stop an aluminium radiometer (334).

342. Were the rotation in moderately rarefied air due to air currents rising from the hot wire, it is difficult to understand why it should be *negative*. To eliminate as far as possible the action of air currents, the apparatus was modified by raising the platinum wire ring so that it was about 5 millims. above the sloping mica vanes, instead of under them, everything else remaining the same.

At low exhaustions, when the wire was ignited, the fly rotated slowly in this direction ∠. The hot wire being above, this is a *negative* movement, as it is opposite to what would be caused by pressure from the wire acting in the vanes, and is therefore quite in keeping with the results obtained with the hot wire beneath.

When the rarefaction reached 0·5 millim. the negative rotation ceased. The fly oscillated to one side and the other without rotating. At higher exhaustions the fly moved *positively* ∠, and this movement increased in strength as the rarefaction increased.

343. When the exhaustion was good, and the vanes were still, a piece of wet blotting-paper was put on the top plate of glass to cool it slightly. Rapid negative rotation took place ∠. Making battery-contact immediately reversed this movement. Touching the top plate of glass with the finger caused positive rotation.

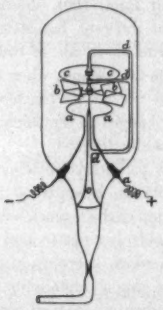
344. These movements are of the same kind as those given by the apparatus in which the wire was beneath the vanes. It is difficult to prevent the action of

* Phil. Trans., Vol. 165, pt. 2, pp. 528–532, March 20, 1875.

† In my first paper on this subject (Phil. Trans., Vol. 164, pt. 2, pp. 513–518, pars. 37–46, August 12, 1873) I also described analogous results with an ignited spiral acting on a balanced brass ball.

air currents: as the sloping vanes are eminently favourable for their detection, I therefore endeavoured to devise an instrument which should rotate without being unduly influenced by air currents, and with which I can get some insight into the direction of the lines of molecular pressure after passing and acting on the moving fly.

Fig. 31.



345. Fig. 31 represents the apparatus. Instead of being open and closed with a plate cemented on, the cylinder is now sealed at the top, so as to enable me to proceed to the highest exhaustion, which cannot be reached unless all the joints and connections are fused together. The platinum wire ring is shown at *a*, *a*, *a*, the sloping mica vanes are shown at *b b*. Above the vanes is a flat disk of clear mica, *c c*, having a glass cap in its centre, and easily rotating on a needle point. The vanes and the mica disk are supported independently of each other on separate needle points which are held in glass rods, *d*, *d*, *d*.

346. In air of the ordinary pressure (Bar. = 761 millims.) on igniting the platinum ring to redness by a current from two Grove's cells, both the vanes and disk rotate in this direction ; that is, the vanes go in the *positive* direction, supposing they are driven round either by molecular pressure from the wire or by air currents. The speed of the vanes is 13·3 revolutions a minute, and that of the disk 1 a minute.

347. I continued the exhaustion. At a pressure of 220 millims. on igniting the wire the rotations are the same as in air, but the speed of the vanes has diminished to 7·5 revolutions a minute, and the disk scarcely rotates at all.

Pressure 80 *millims.*—The disk will not rotate, but oscillates a little to and fro. The vanes still rotate *positively* at a speed of 1·5 revolutions a minute.

Pressure 34 *millims.*—The disk has ceased to move. The vanes move very slightly in the *positive* direction when the apparatus is tapped.

Pressure 19 *millims.*—No movement whatever. The disk and vanes are as still when the wire is ignited as when it is cold.

348. *Pressure* 14 *millims.*—The disk is still stationary. The vanes move very slowly in the *negative* direction .

Pressure 1 *millim.*—The disk has commenced to rotate in the same direction as the vanes, at a speed of 3 revolutions a minute. The vanes have been gradually increasing in speed as the exhaustion has progressed until they now rotate at a speed of 43 revolutions a minute in the negative direction .

349. These results are sufficient to show that the negative movement met at moderately low exhaustions (339, 342) is not caused by air currents. As shown in par. 342, the effect of a current of hot air rising from the platinum ring should be the same as that of molecular pressure coming from the ring. If the molecular wind may be supposed to blow the vanes round in a *positive* direction a molar wind should certainly act in the same manner. The present apparatus shows that this supposition is correct. In air at normal density the action of air currents is strong, blowing the vanes round *positively*. As the density diminishes, the strength of the air currents lessens likewise, until at a pressure of 19 millims. the ascending current of hot air has not strength enough to blow the vanes round positively, in opposition to the friction of the needle point, and possibly in opposition to the tendency to a negative movement which at a little less pressure begins to be apparent.

350. *Pressure* 706 *millionths of an atmosphere.**—The disk and the vanes both rotate in the same direction; the disk making 10 revolutions and the vanes 40 revolutions a minute *negatively* .

Pressure 400 *millionths of an atmosphere.*—Movements and direction as at 706 millionths. The disk making 12 and the vanes 25 revolutions a minute *negatively*.

Pressure 294 *millionths of an atmosphere.*—At this pressure the speed of the disk and of the vanes is exactly alike. They rotate together in the same direction as when last observed, as if they were fixed to the same axis, at a speed of 12·5 revolutions a minute .

351. *Pressure* 141 *millionths of an atmosphere.*—Up to this observation the vanes have been gradually diminishing whilst the disk has been increasing in speed. At this pressure, under the influence of the ignited wire, the disk rotates at a speed of 26 revolutions a minute. The vanes, however, do not rotate at all, but oscillate a little as if under the influence of two opposing forces.

352. *Pressure* 129 *millionths of an atmosphere.*—Between this experiment and the last a sudden change has occurred. The vanes which then were still now rotate rapidly in the *positive* direction with a speed of 100 revolutions a minute. The disk continues to rotate in the same direction as before, but with slightly diminished speed (18·5 revolutions a minute) . It is probable that some of the speed of the disk is

* At low exhaustions I speak of millimetres of pressure, but at high exhaustions I prefer to count in millionths of an atmosphere. The inconvenience of using two units of measure is less than that of employing one system for both ends of the scale.

quenched by the rapid movement of the vanes in the opposite direction. As is already shown,* the viscosity of air at a rarefaction of 129 millionths of an atmosphere is only a little less than its viscosity at the normal density; hence the vanes, at a speed of 100 revolutions a minute, must exert a considerable drag on the opposite rotation of the disk.

353. *Pressure* 82·5 *millionths of an atmosphere.* The disk has again increased in speed, now revolving at the rate of 24 turns a minute. The speed of the vanes is too great to count; a rough estimate shows that the rate is about 600 revolutions a minute. The direction of the vanes is positive, whilst the disk rotates in the opposite direction .

The increased speed of the disk, in spite of the greater rapidity of the vanes tending to drag it round in the opposite direction, shows that the viscosity of the residual gas is diminished. On referring to my preliminary note,† it will be seen that the viscosity of air has commenced to diminish rapidly at 82 millionths of an atmosphere, and after that the fall is very quick. To carry these experiments to a much higher exhaustion, some modification in the apparatus is needed; the heat must be less concentrated, so as to diminish the speed, since it is useless to continue observations when the rate of rotation cannot be estimated. The following apparatus was accordingly fitted up, to enable me to get the observation of speed, together with the viscosity of the internal air.

As the results obtained with this new apparatus are more numerous than with the previous apparatus, I will for the present defer comments on the different motions of the disk and vanes.

354. The apparatus is the most complicated I have yet used, and in order to make clear the relative bearing of the different observations I will describe it in detail, and give a drawing of it (fig. 32). This will serve a double purpose; it will enable my description to be clearly understood, and it will illustrate, better than is possible by mere words, the great complexity of apparatus frequently requisite to obtain, in a physical investigation, results which can be expressed in a few short paragraphs.

355. The pump is shown at *a b*, the upper part only being represented. It does not differ materially from the form of pump described by Mr. C. H. Gimingham in the 'Proceedings of the Royal Society,' No. 176, 1876. It has, however, five fall tubes instead of three, and is fitted with a small radiometer, *c*, and a McLeod measuring apparatus, *d e*, to enable me to ascertain the degree of exhaustion in the apparatus. The facility of working has been considerably improved by the introduction of phosphoric anhydride‡ instead of sulphuric acid for absorbing aqueous vapour. The phosphoric anhydride dries gases better than sulphuric acid does, and evolves no vapour, whereas at the highest exhaustions sulphuric acid evolves a perceptible vapour.

* Proc. Roy. Soc., Nov. 16, 1876, No. 175, p. 304.
† Do. Do. p. 305.
‡ Do. Do. p. 306.

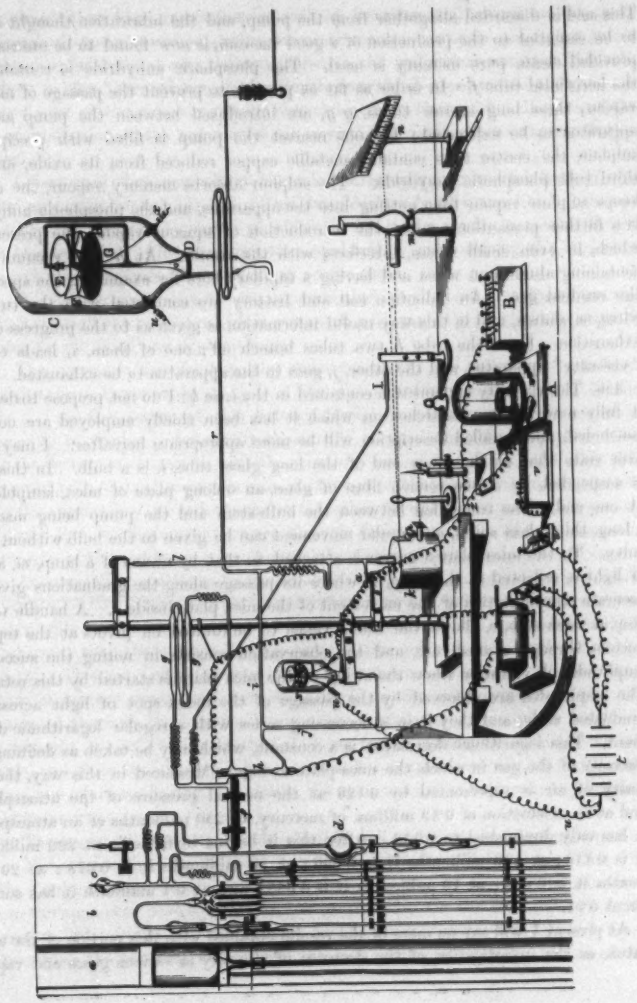


Fig. 32.

This acid is discarded altogether from the pump, and the lubrication thought at first to be essential to the production of a good vacuum, is now found to be unnecessary, provided clean, pure mercury is used. The phosphoric anhydride is contained in the horizontal tube *f*. In order as far as possible to prevent the passage of mercury vapour, three long narrow tubes, *g g*, are introduced between the pump and the apparatus to be exhausted; the one nearest the pump is filled with precipitated sulphur, the centre tube contains metallic copper reduced from its oxide, and the third tube phosphoric anhydride. The sulphur absorbs mercury vapour, the copper keeps sulphur vapour from getting into the apparatus, and the phosphoric anhydride is a further precaution against the introduction of aqueous vapour, the presence of which, in even small traces, interferes with the results. At *h* is a vacuum tube, containing aluminium wires and having a capillary bore for examining the spectra of the residual gas. An induction coil and battery are connected with the tube by wires, as shown, and in this way useful information is given as to the progress of the exhaustion. From the tube *h* two tubes branch off; one of them, *i*, leads to the "viscosity" apparatus, and the other, *j*, goes to the apparatus to be exhausted.

356. The viscosity apparatus is contained in the case *k*; I do not propose to describe it fully now, as the researches on which it has been chiefly employed are not yet concluded, and detailed description will be more appropriate hereafter. I may however state that at the lower end of the long glass tube, *l*, is a bulb. In this bulb is suspended, by a fine torsion fibre of glass, an oblong plate of mica, lampblacked at one end. The connexion between the bulb-stem and the pump being made by a long, thin, glass spiral, an angular movement can be given to the bulb without difficulty. To the mica plate a mirror is attached, so that by means of a lamp, *m*, a spot of light is reflected to the scale, *n*, where its passage along the graduations gives an accurate representation of the movement of the mica plate inside *k*. A handle with a stop at each side, *o*, allows the whole vessel to be rotated on pivots at the top and bottom, through a small arc, and the observation consists in noting the successive amplitudes of vibration when the swing of the mica plate is started by this rotation. The amplitudes are observed by the passage of the index spot of light across the graduated scale, and they form a decreasing series with a regular logarithmic decrement. This logarithmic decrement is a constant, which may be taken as defining the viscosity of the gas in which the mica-plate swings. Measured in this way, the viscosity of air is represented by 0·126 at the normal pressure of the atmosphere; and at an exhaustion of 0·19 millims. of mercury, or 250 millionths of an atmosphere, it has only diminished to 0·112. After this it begins to fall off: at 200 millionths it is 0·110; at 100 millionths it is 0·096; at 50 millionths it is 0·078; at 20 millionths it is 0·052; at 10 millionths it is 0·035; and at 0·1 millionth it has sunk to about 0·01.

At present I will say no more of the results obtained with this portion of the apparatus, as the investigation of the decrease of viscosity in various gases and vapours

when subjected to high rarefaction is still in progress, and owing to the great expenditure of time required in getting accurate results it may be some time before the research is finished. I may, however, refer to the preliminary notice on this subject, given in the 'Proceedings of the Royal Society,' November 16, 1876, for an account of some of the viscosity results obtained at that time, with a diagram of the curves of diminution of the viscosity of air, oxygen, and hydrogen, as the rarefaction proceeded.

357. I have said that one-half of the mica plate swinging in the bulb of the viscosity apparatus is lampblacked. This lampblacked half is opposite a tube, *p*, furnished with a shutter, by means of which the light of a candle, *q*, can be thrown on the blacked plate. The repulsion thus produced is measured by the successive swings and final deflection of the index ray on the scale.

358. When other gases than air are experimented on they are introduced into the apparatus through the tube, *r*, which is connected with gas reservoirs and appropriate apparatus for purifying and drying the gas.

359. The apparatus, *s*, more especially under examination, is sealed to the tube, *j*. It is shown on a larger scale at C, D. The platinum ring in *s* is ignited by the battery *t*. As the power of this battery varies considerably during a series of experiments, to render it practically constant I adopted the following plan. One pole of the battery is connected with the wire, *u*, running direct to *s*; the other pole is connected with a box of resistance coils, *v*, through which the current passes; it then goes to the contact key, *w*, and thence to the other wire, *x*, up to *s*. By depressing the contact key, *w*, the current passes through the wire ring in *s*, and ignites it. The strength of the current passing through the ring can be regulated to a nicety by adding or subtracting resistance by means of the coils at *v*. At *y* and *z* wires shunt off a portion of the battery current and conduct it to the galvanometer A and the resistance coils B. The galvanometer is a very delicate one, and the resistance in B is so adjusted that the current flowing through the galvanometer shall deflect the needle 18°. This being adjusted once for all the resistance B is never altered. Any variation of battery power will now show itself on the galvanometer A, and the resistance of the coils, *v*, is immediately altered until the galvanometer needle is again brought to 18°. This method I have found sufficiently accurate for all purposes, and since its adoption I have been able to experiment day after day with the certainty of always having, practically, the same amount of battery power igniting the platinum ring.

360. The apparatus, *s*, containing the rotating disk and vanes is shown enlarged at C, D. The construction of glass bulb, the rotating mica plate, E, the sloping vanes, F, and the platinum ring, G, connected with the outer wires, *u*, *x*, do not differ from those in the apparatus shown in fig. 31, paragraph 344. On the top of the platinum ring rests a disk of mica, H, lampblacked on the upper surface; this cuts off direct radiation from the hot ring, and diffuses the heat somewhat over the surface of the

black mica. Instead, therefore, of the molecular pressure starting from the wire, as in previous experiments, the blacked mica now becomes the driving surface.

361. The whole of this complicated arrangement of apparatus is connected together by actual fusion of the glass tubes one to another; no joint whatever occurs in any part, and a certain point of exhaustion being once attained, I can leave the apparatus to itself with the certainty that no leakage from without can occur. The apparatus by which the gas is introduced has, it is true, a tap, but when it has effectually done its work this tap is disconnected from the rest of the apparatus by fusion.

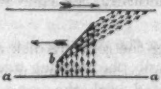
362. An observation with this apparatus is taken in the following way. Having arrived at a point when a depression of the contact key tells me, by the behaviour of the rotating disks, that a useful observation can be taken, the pressure is first measured in the McLeod apparatus. The viscosity of the gas is then observed, and next the repulsion exerted on the viscosity-plate by the candle. At a very high exhaustion the appearance of the induction spark in the tube, *h*, is also noted, together with the spectrum given by it. The strength of the current being first regulated by the resistances, *v*, the key, *w*, is pressed down, and the direction and speed of the vanes and disk in *s* are taken by a chronograph recording to tenths of a second. Frequently duplicate or triplicate observations are taken at each pressure, time being allowed to elapse between the observations for the apparatus to become cool.

363. In describing the direction of rotation of the vanes and disk, I shall call the direction they take at high exhaustions the *positive* direction, and the contrary the negative; thus, the positive rotation of the disk and vanes will be as follows:—

364. At a pressure of 761 millims., when the wire is heated, positive rotation takes place both of the disk and vanes. As the exhaustion increases the positive rotation of the disk diminishes, then stops, and at 100 millims. pressure the disk commences to rotate *negatively*, or the same way as the vanes go, thus: . The viscosity of the air is 0·124.

The probable explanation of these actions is as follows:—In air at the normal density the red hot ring causes air currents to rise; these strike the vanes and cause them to rotate positively. The sloping vanes also cause a deflection in the ascending current of hot air, and the disk, therefore, is struck at an angle by the air currents, causing it to rotate the opposite way to the vanes. The diagram (fig. 33) represents

Fig. 33.



this action. *a*, *a*, is the hot wire ring, the small arrows show the direction of the rising currents of hot air, which, striking against the vanes, are deflected in such a way as to cause the disk to rotate. The direction of rotation is shown by arrows.

At 100 millims. pressure the ascending current of hot air is not strong enough to turn the disk round, and it is therefore carried along with the vanes by the viscosity of the air, which is practically the same as at 760 millims.

At a pressure of 10 millims. the vanes become still, but the disk rotates very slowly *negatively*.

At 1 millim. pressure, the disk still rotates slowly negatively, whilst the vanes will not move.

365. *Pressure* 824 *millionths of an atmosphere.*—When the current is first turned on, the vanes give half a revolution in the negative direction, ∠, they then stop. The disk continues to rotate in the *negative* direction, ⊖. An observation of viscosity at this pressure gives the figure 0·106. The repulsion produced by the candle on the viscosity plate shows a force of 4·8.

It will be observed that the first movements of the vanes at this pressure is in the *negative* direction, but this soon stops. On referring to par. 348, where I describe an experiment on a similar apparatus, but where the platinum wire is uncovered, and the heat therefore more intense, it will be seen that the negative tendency is strong enough to cause continuous rotation of the vanes. This negative rotation of the vanes begins to be apparent at 14 millims. pressure; it is very strong at 760 millionths of an atmosphere (350), and disappears at about 140 millionths of an atmosphere (351). Between a pressure of 294 millionths of an atmosphere and 129 millionths of an atmosphere, there is a great change in the movement of the vanes when under the influence of the hot, naked, platinum ring, the rotation changing from 12·5 revolutions a minute *negatively* at the former pressure, to 100 revolutions a minute *positively* at the latter pressure. How narrow are these limits may best be seen by converting them into decimals of a millimetre: the negative rotation is good at 0·2234 millim., whilst the positive rotation is very strong at 0·0978 millim. The negative rotation between the above-named limits is not so apparent in the apparatus where the platinum wire is covered with mica (345) as when the naked wire is used. This behaviour offers an anomaly which I shall endeavour to clear up at a future time. As I do not believe in *attraction*, and consider that all these movements are caused by a force having the action of a *push*, many experiments now in progress will be required to explain the difficulties of this negative action.

366. *Pressure* 530 *millionths of an atmosphere.*—A little negative rotation of the vanes takes place on first making contact, and they then become stationary. The disk rotates at a speed of one revolution a minute in the *negative* direction, ⊖. The viscosity of the air is 0·104, and the candle repulsion = 7·1.

367. *Pressure* 470 *millionths of an atmosphere.*—The vanes remain stationary. On first making contact the disk makes 1½ revolution in the *positive* direction, and then rotates continuously in the *negative* direction, at the rate of one-third of a revolution a minute. Viscosity = ·102. Candle repulsion = 8·2.

368. *Pressure* 388 *millionths of an atmosphere.*—No movement of the vanes on making contact. Negative rotation of the disk, at a speed of 1·25 revolutions a minute. Viscosity = 0·103. Candle repulsion = 9·3.

369. *Pressure* 212 *millionths of an atmosphere.*—On first making contact the vanes and disk move in the same direction, the vanes going ¼ revolution *negatively*, and the disk ½ revolution *positively*, thus . The vanes then remain still, but the disk rotates negatively, at a uniform speed of 1 revolution a minute. Viscosity = ·099. Candle repulsion = 12·7.

370. *Pressure* 118 *millionths of an atmosphere.*—The vanes now rotate continuously in the *positive* direction at the rate of 19 revolutions a minute. The disk first rotates *positively*—*i.e.*, in the opposite direction to the vanes—then stops and rotates very slowly the same way as the vanes. Viscosity = ·092. Candle repulsion = 24.

371. *Pressure* 94 *millionths of an atmosphere.*—On igniting the wire, the general action is as last described, but the disk continues the preliminary *positive* rotation for a longer time before it takes up its negative rotation . The vanes rotate *positively* at a rate of 30 revolutions a minute. Viscosity = ·089. Candle repulsion = 29.

372. *Pressure* 59 *millionths of an atmosphere.*—The positive rotation of the disk now continues, at a uniform speed of 2·5 revolutions a minute, without changing to negative, as in the last two cases. The vanes move *positively*, at a rate of 68 revolutions a minute . Viscosity = ·080. Candle repulsion = 35·5.

When the disk and vanes are moving *positively* at a uniform speed, if the battery current is turned off so as to let the platinum ring cool, the positive motion of the disk soon stops, the vanes continuing to rotate. The disk now changes its direction and rotates *negatively* the same way as the vanes; its velocity soon becomes equal to that of the vanes, and they then both rotate together as if fixed to the same axis.

This change of direction in the disk and its subsequent following the vanes are due to the viscosity of the air causing the rapidly moving vanes to drag the disk round with it.

373. *Pressure* 14 *millionths of an atmosphere.*—The positive rotations of both disk and vanes continue as in the last experiment, the speed increasing. The vanes rotate 150 times a minute, and the disk 10 times a minute . Viscosity = ·044. Candle repulsion = 27.

374. *Pressure* 11 *millionths of an atmosphere.*—The positive rotations are the same as before. The velocity of the vanes is about 600 revolutions a minute, but it is difficult to register accurately these high speeds. The disk rotates 12 times a minute. Viscosity = ·039. Candle repulsion = 23·5.

At this pressure, when the battery is turned off, and the wire allowed to cool, the disk continues its positive movement for a considerable time. The viscosity of the rarefied air is now only ·039, and the drag of the vanes on the disk takes longer to exert its influence than when the viscosity was ·08.

375. *Pressure 6 millionths of an atmosphere.*—The speed of the vanes is far too great to count, and their shape is scarcely distinguishable owing to the velocity. The disk rotates steadily at a rate of 22 turns a minute . Viscosity = ·029. Candle repulsion = 16.

376. *Pressure 2 millionths of an atmosphere.*—By reason of their great speed, the vanes are now invisible, except as a nebulous ring. The disk makes 30 revolutions a minute. Viscosity = ·020. Candle repulsion = 10.

377. *Pressure 0·4 millionth of an atmosphere.*—The vanes and disk rotate as at the last pressure. There is no apparent diminution in the speed of the vanes, and the disk is going at the rate of 31 revolutions a minute. Viscosity = ·016. Candle repulsion = 6.

378. I could not get a higher exhaustion in this experiment, so I filled the apparatus with pure hydrogen. This was effected, previous to the first experiment, by sealing on to the pump a tube, shown at I, containing palladium foil saturated electrolytically with hydrogen. This alloy is perfectly stable in the cold at the highest exhaustions (233), but when gently heated the hydrogen is given off in quantities which can be easily regulated by careful manipulation. The gas was allowed to depress the gauge about 50 millims. The pump was then worked till a high exhaustion was reached, and more hydrogen evolved. After two or three heatings and pumpings, the residual air was assumed to have been washed out, and the observations in hydrogen were commenced.

379. At a pressure of 5 millims., when the platinum ring is ignited, the vanes are still, but the disk rotates in the *negative* direction. At 1·25 millims. both vanes and disk are still. At ·8 millim. the vanes keep stationary as before, but the disk assumes a *positive* rotation.

At ·6 millim. positive rotation of the vanes commences, and that of the disk continues at a little greater speed than before .

At 47 millionths of an atmosphere the positive rotation of the vanes is too rapid to count. That of the disk is 10 revolutions a minute.

380. *Pressure 8 millionths of an atmosphere.*—When the current is first turned on, the vanes commence to rotate rapidly in the positive direction, and the disk revolves more slowly in the positive direction. The speed of the vanes gradually increases up to a maximum of at least 1000 turns a minute; and during this increase of speed the disk revolves slower and slower, until, when the vanes rotate at the highest velocity, the disk is quite still. The reason of this peculiar behaviour is probably this: the enormous speed of the vanes, acting on the disk through the viscosity of the residual gas, causes a tendency to *negative* rotation—*i.e.*, in the same direction as the vanes; this tendency to negative rotation balances the rotation due to the tangential action of the molecular pressure, which, deflected from the sloping vanes, would turn the disk *positively*.

By gently tilting the apparatus, I can make the rotating vanes strike the support. They are thus stopped, and the disk immediately commences its *positive* rotation. The drag of viscosity being removed, molecular pressure prevails.

The deflection of the molecular pressure, by the vanes, on to the disk, turning the disk in the direction opposite to that of the vanes, may also be represented by fig. 33, par. 364, which shows the similar action of a current of hot air.

381. Whilst this action was going on, the disk stationary and the vanes in full rotation, I turned off the battery current. The vanes continued to move in the positive direction, and when their speed had sunk to about 100 revolutions a minute, the disk commenced to turn with the vanes, being dragged round by the viscosity, there now being no molecular pressure tending to give positive movement.

382. *Pressure* 1·4 *millionth of an atmosphere.*—On first turning on the battery, both the vanes and disk turn *positively*. As the speed of the vanes increases, that of the disk diminishes; but when the vanes are rotating at their uniform maximum speed, the disk does not quite stop but moves a little positively. The viscosity of the hydrogen at this rarefaction is only ·0168 (as against ·057 at the normal pressure), and it is therefore not enough to quite neutralise the action of the molecular pressure. On turning the battery off, the vanes nearly stop before they exert any drag on the disk.

At this pressure the spectrum of hydrogen in the vacuum tube only shows one line in the green (the F line), and that very faint.

Fig. 34.

383. In fig. 34 I have plotted down the observations taken in air vacua in this appa-

ratus from the data in paragraphs 369 to 377. They are connected together by lines forming curves; in the curve representing the "candle repulsion" I have interpolated a few observations from other experiments to fill up a gap between 59-millionths and 14-millionths, and to give a better idea of the direction the true curve would take.

The "candle repulsion" and the "viscosity" curves are similar to those already published in the 'Proceedings of the Royal Society.'* In describing these curves in November, 1876, I said that the viscosity of the residual gas in an air vacuum was practically constant up to an exhaustion of 250 millionths of an atmosphere, having only diminished from 0·126 at the normal pressure of the atmosphere to 0·112. It now begins to fall off, and at 0·1 of a millionth of an atmosphere it has fallen to about 0·01. Simultaneously with this decrease in the viscosity, the force of repulsion exerted on a black surface by a standard light varies. It increases very slowly till the exhaustion has risen to about 70 millionths of an atmosphere; at about 40 millionths the force is at its maximum, and it then sinks very rapidly, till at 0·1 millionth of an atmosphere it is less than one-tenth of its maximum.

384. The diagram (fig. 34) entirely confirms the observations described last year. In order to keep the diagram within reasonable limits, I have omitted the observations at lower exhaustions than 118 millionths of an atmosphere, but from that point upwards the parallelism is close. The candle repulsion rises to a maximum somewhere between 59 and 14 millionths of an atmosphere, and then rapidly sinks up to the highest exhaustion obtained. Simultaneously the viscosity drops rapidly at the high exhaustions. From these observations I might be justified in assuming that it would be a general law that above 40 millionths of an atmosphere the repulsion resulting from radiation would fall off as the exhaustion got nearer absolute, and this idea would be greatly confirmed by the experiment with the radiometer described in paragraph 334, and graphically illustrated in the curve on fig. 28.

It now seems that this generalisation would be too hasty, and the utmost that can be said is that the statement is true for the particular instances described. When, instead of the feeble intensity of radiation which can penetrate glass from a candle some inches off, I substitute the intense energy of a red hot platinum wire a few millimetres off, the answer given to my interrogations is very different. There is now no maximum at 40 millionths, and subsequent rapid falling off, but a steady increase of speed from 67 revolutions a minute at 59 millionths, 150 revolutions at 14 millionths, 600 revolutions at 11 millionths, up to over 1000 revolutions at 6 millionths, and still increasing speeds at 2 millionths and at 0·4 millionth. At an exhaustion where the repulsion set up by the candle is least, that caused by the hot wire is greatest.

In air, at still higher exhaustions, I could detect no falling off of speed, but when the residual gas was hydrogen I thought that there was a diminution of velocity after 1 millionth of an atmosphere had been reached.

* No. 175, 1876, page 305.

385. The term "vacuum" has till recently been greatly misapplied. Formerly, an air-pump, which would diminish the volume of air in the receiver 1000 times, was said to produce a vacuum. Later, a perfect vacuum was said to be produced by chemical absorption and by the Sprengel-pump, the test being that electricity would not pass when the air is rarefied a few hundred thousand times.

386. It is generally taken for granted that when a number is divided by 10,000,000 the quotient must be necessarily small, whereas it may happen that the original number is so large that its division by 10,000,000 seems to make little impression on it. According to Mr. JOHNSTONE STONEY,* the number of molecules in a cubic centimetre of air at the ordinary pressure is probably something like 1000,000000,000000,000000. Now, when this number is multiplied by 0·0000004, or in other words divided by 2,500000, there are still 400,000000,000000 molecules in every cubic centimetre of gas at the highest exhaustion to which I carried the experiment illustrated in fig. 34—a rarefaction which would correspond to the density of the atmosphere about seventy-five miles above the earth's surface, assuming that its density decreases in geometrical progression, as its height increases in arithmetical progression (21 *note*, 74). Four hundred billion molecules in a cubic centimetre appear a sufficiently large number to justify the supposition that when set into vibration by a white hot wire, they may be capable of exerting an enormous mechanical effect.

* Phil. Mag., vol. xxxvi. p. 141.

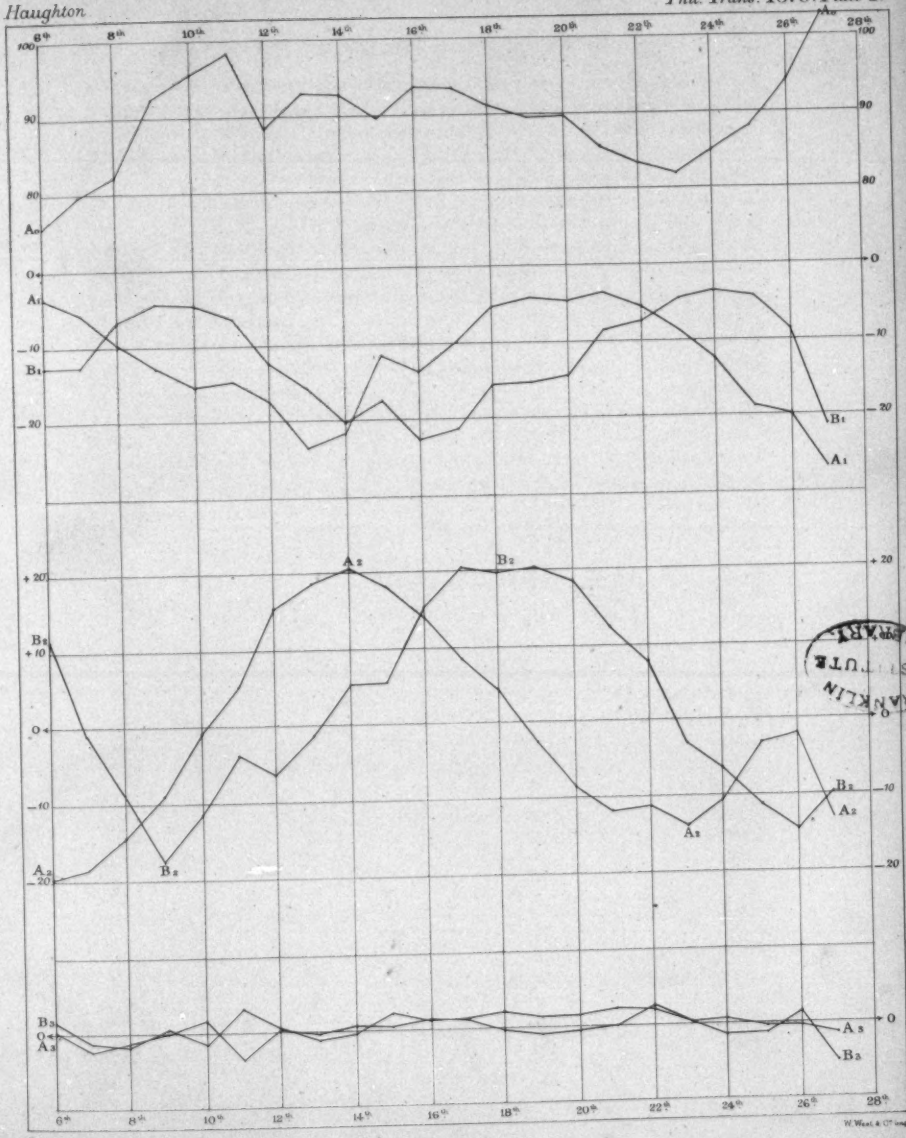


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Fig. 1.

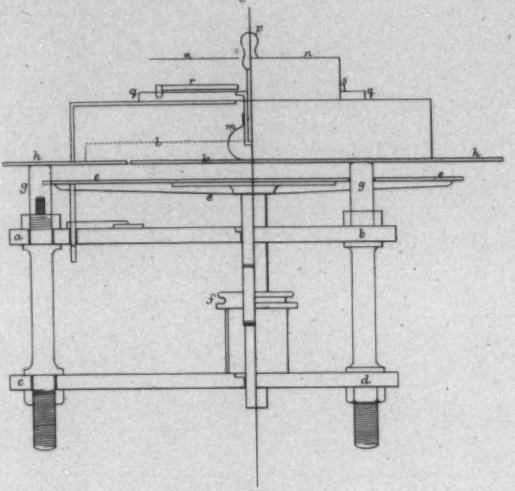

Fig. 2

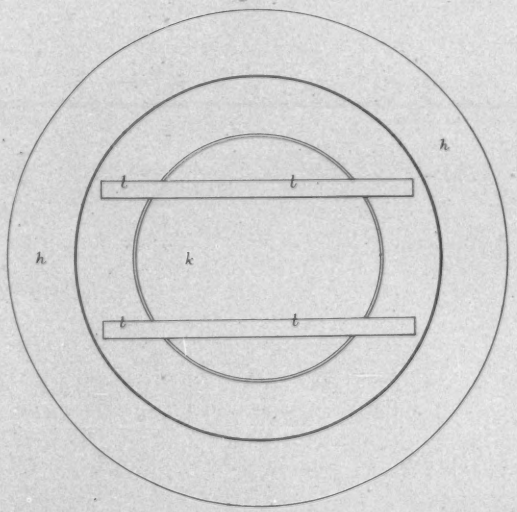

Fig. 4.

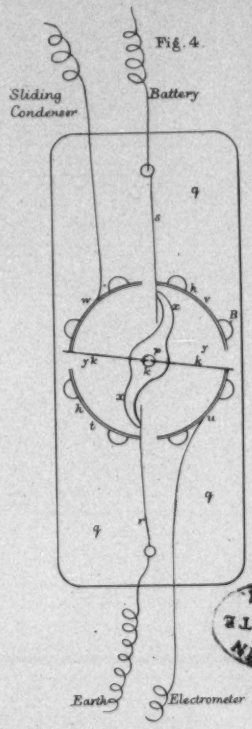

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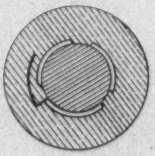
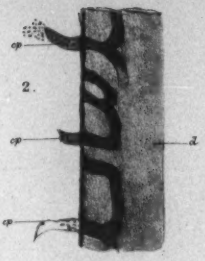
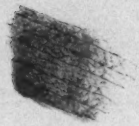
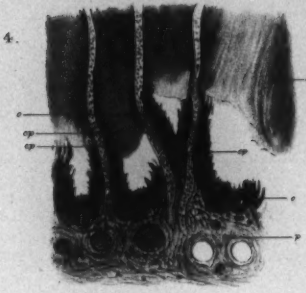
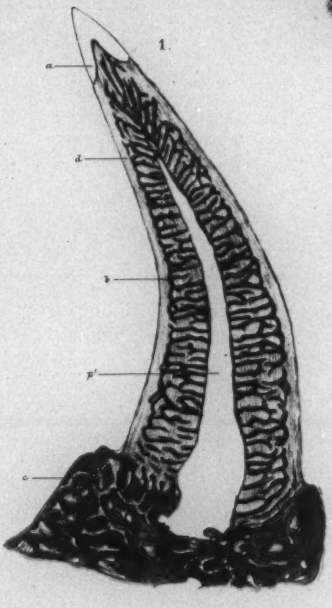
Fig. 3.











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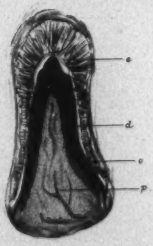

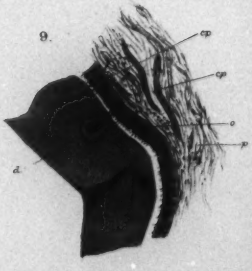

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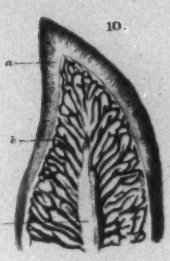

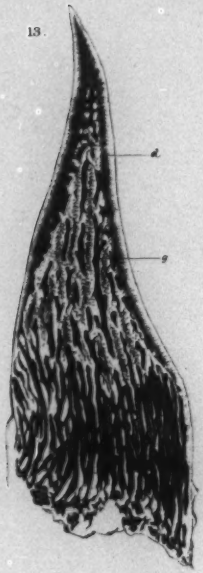

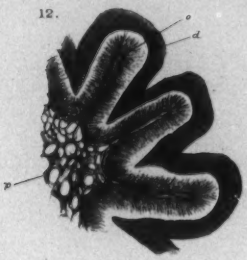

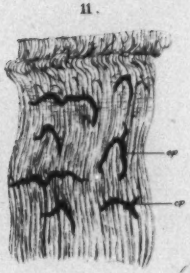

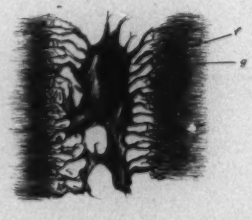

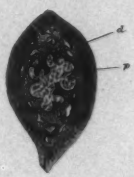

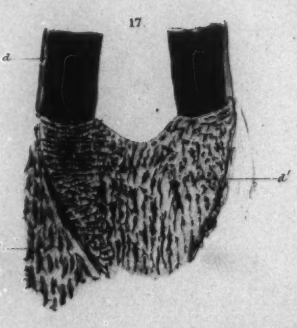

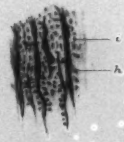

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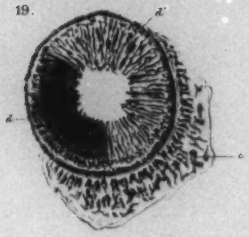

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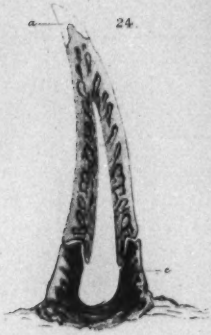

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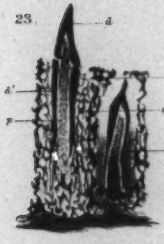

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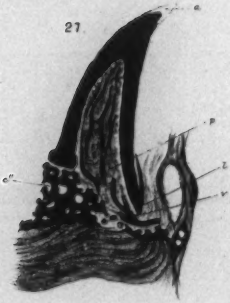

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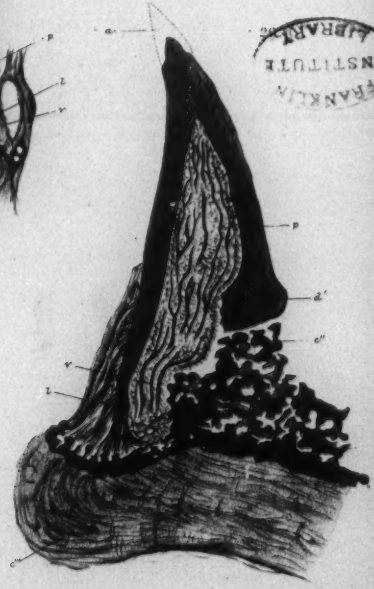

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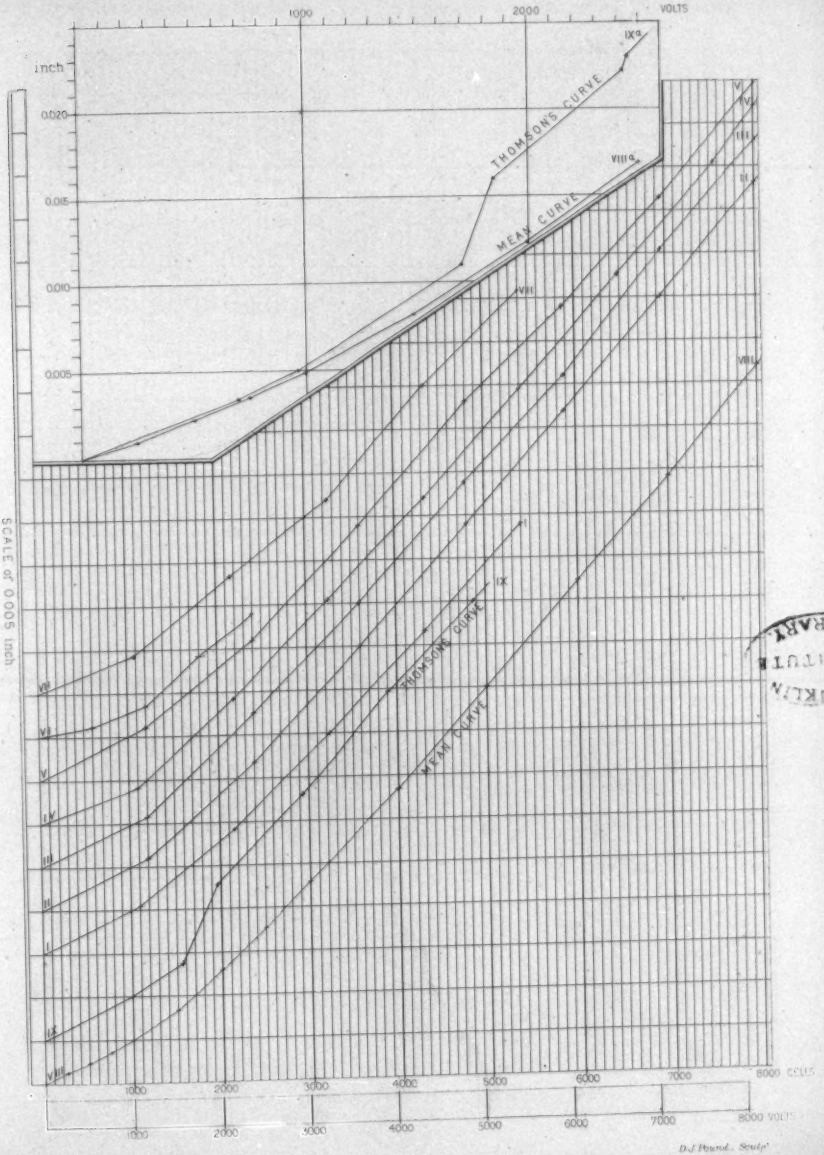
CURVES OF LENGTH OF SPARK BETWEEN SPHERICAL SURFACES.



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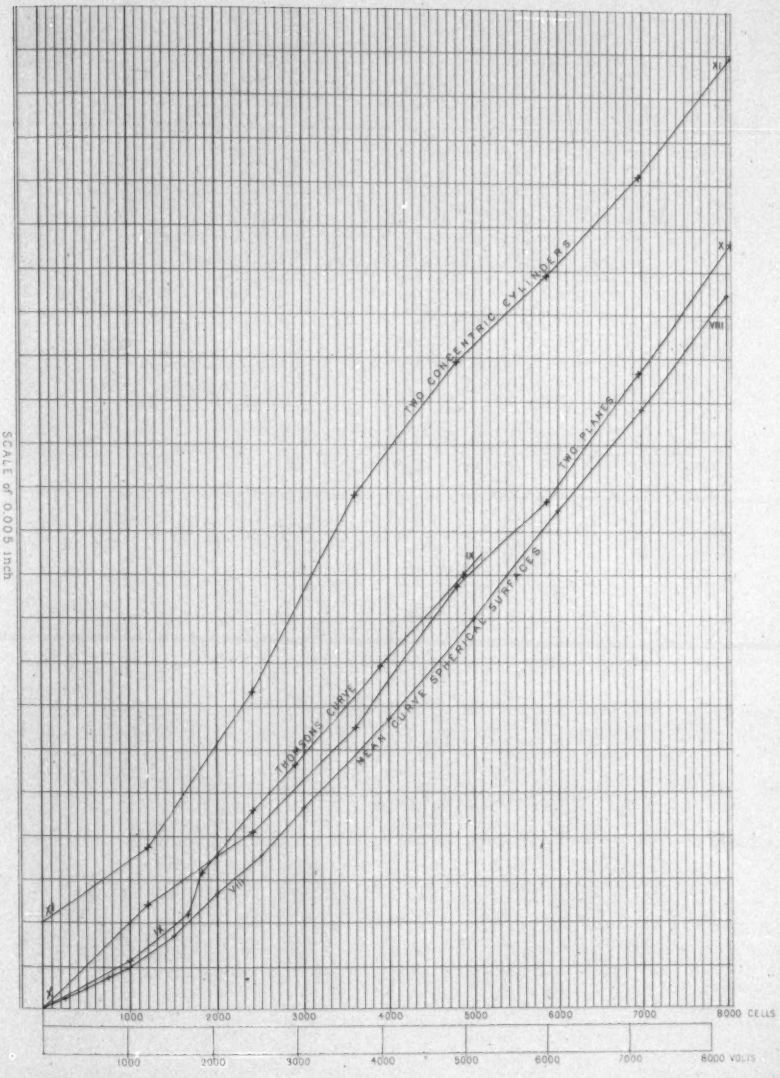
CURVES OF SPARK BETWEEN PLANE SURFACES & CONCENTRIC CYLINDERS.



Warren De La Rue, del.

D.J. Pound, Sculpt.

CURVES OF LENGTH OF SPARK BETWEEN A POINT AND A DISC.

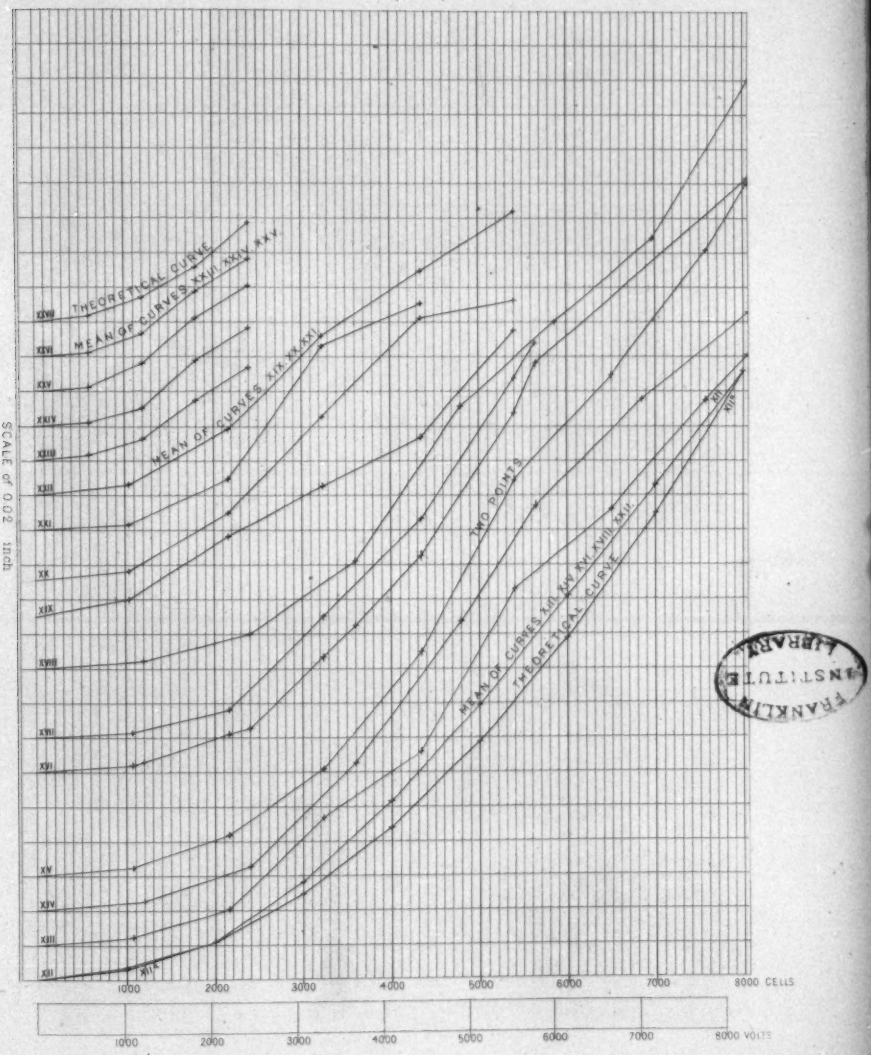


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Fig. 1.

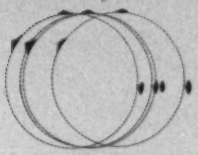
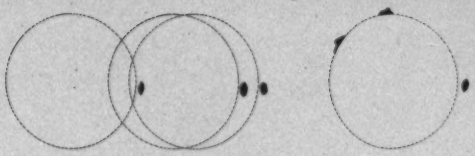


Fig. 2.



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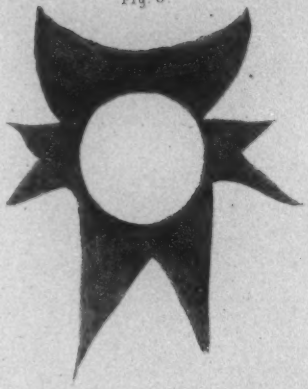

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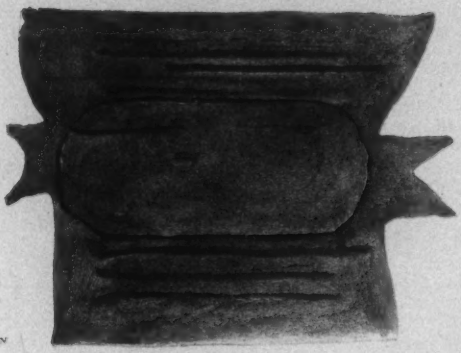

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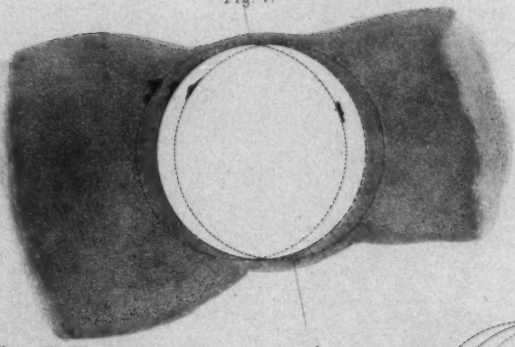

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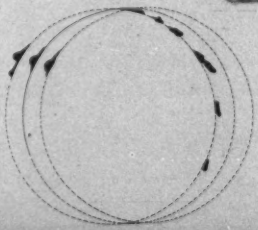

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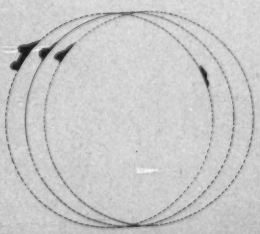

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Fig 8.

Fig 9.

Fig 10.
Exposure 2 Seconds.

Fig 11.
Exposure 4 Seconds.

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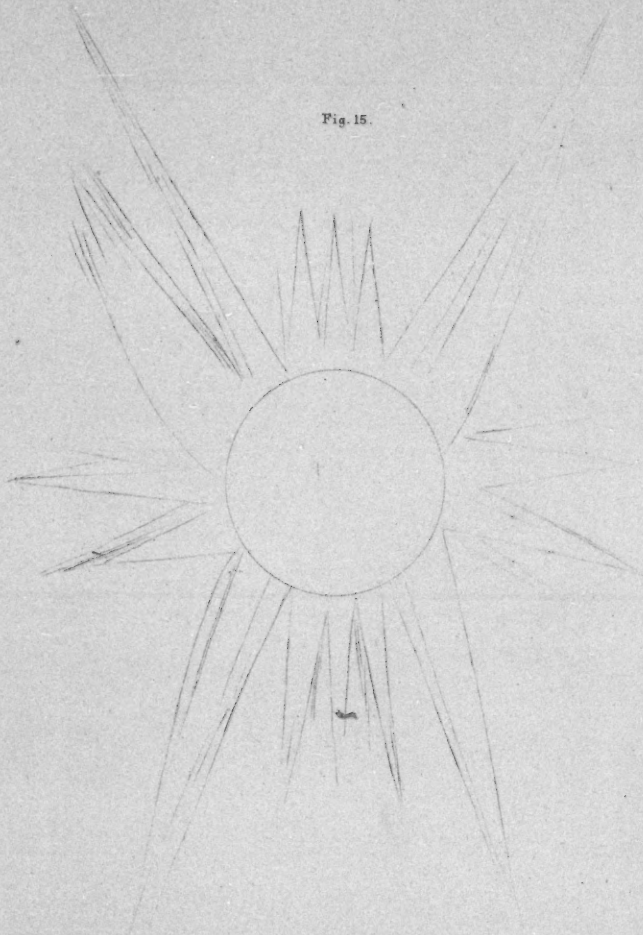
Fig 12.
Exposure 8 Seconds.

Fig 13.
Exposure 16 Seconds.

Fig. 15.



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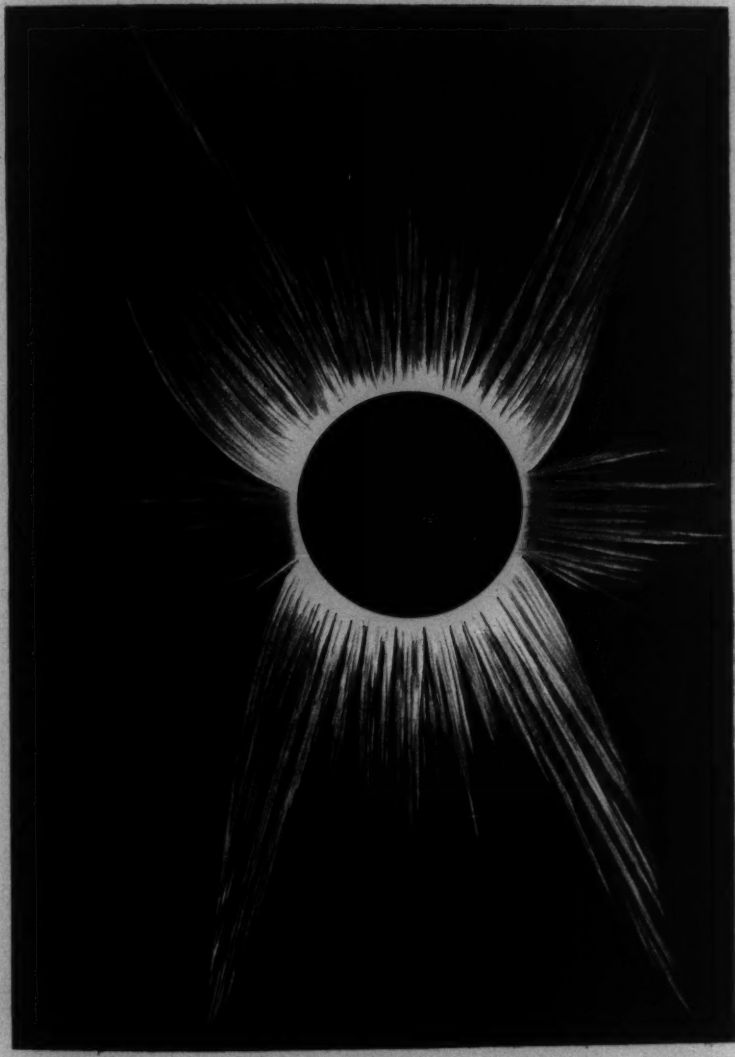

W. West & Co.ᵗᵈ lith.

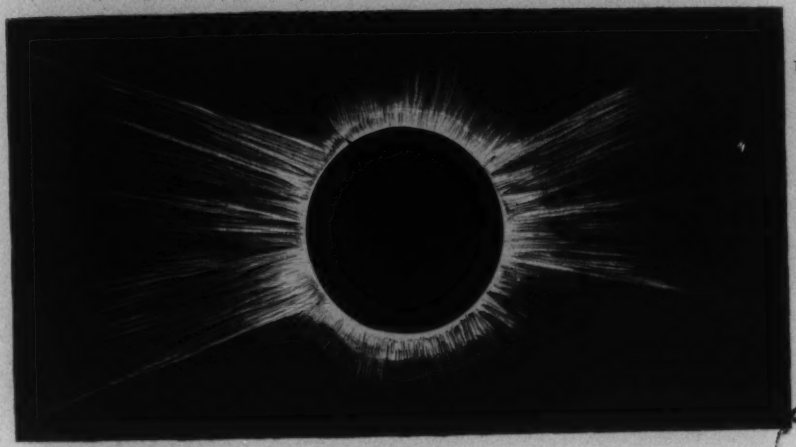

Fig. 14.

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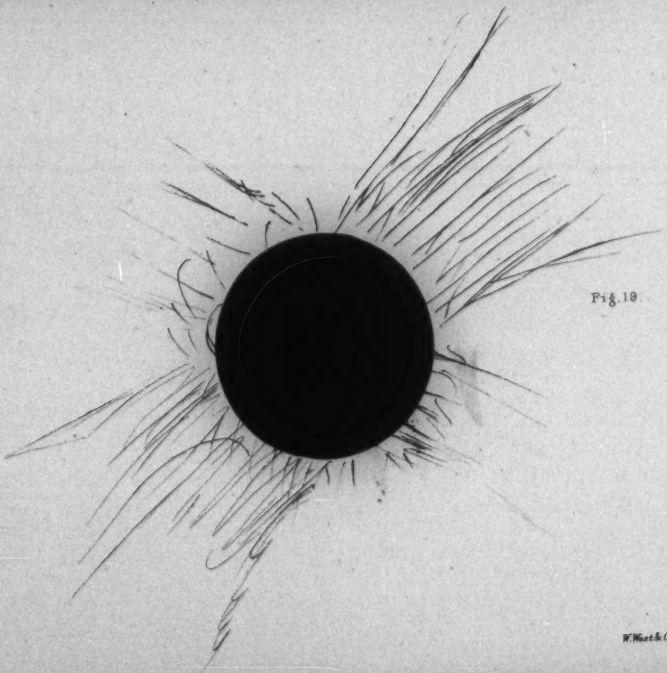
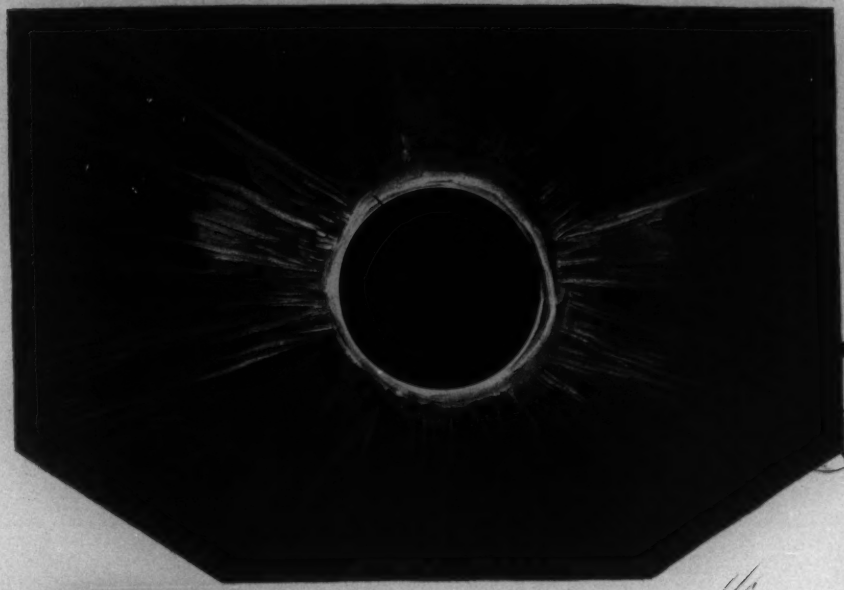


Fig. 19.

W. West & Co. lith.



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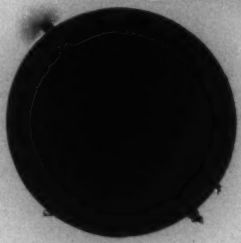

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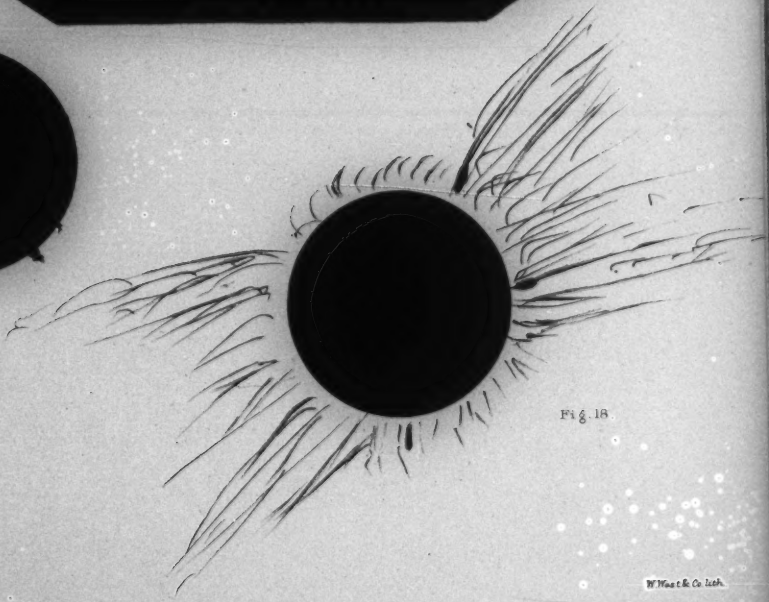
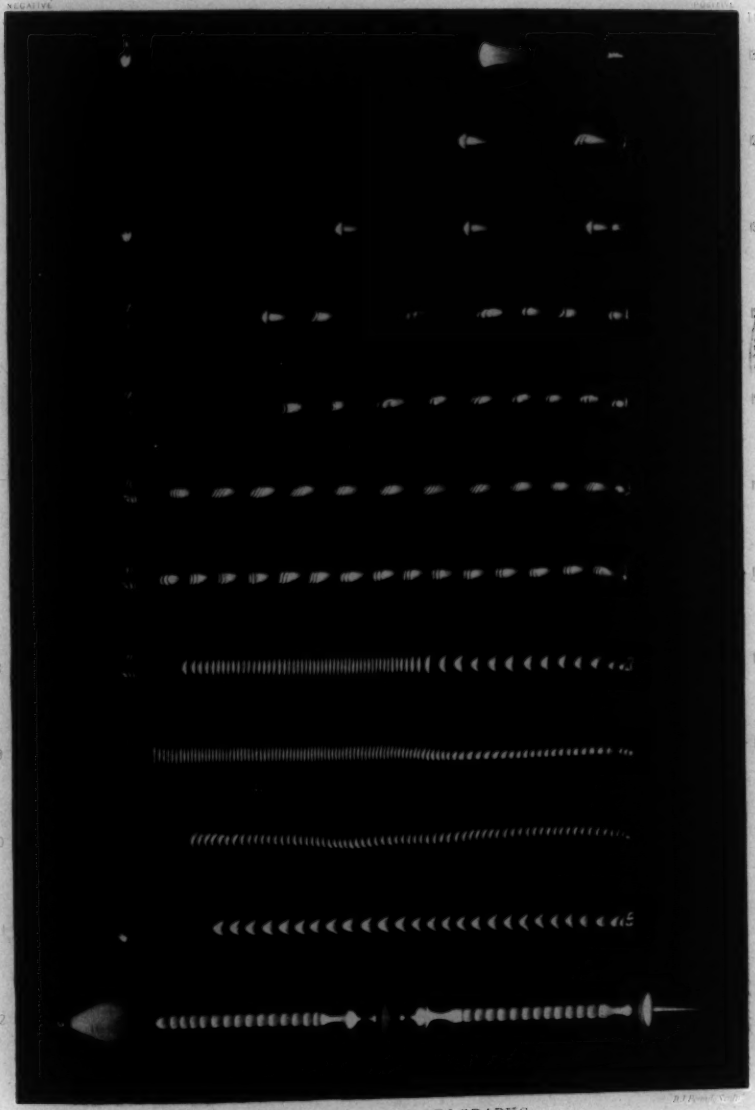


Fig. 18.

W. West & Co. lith.



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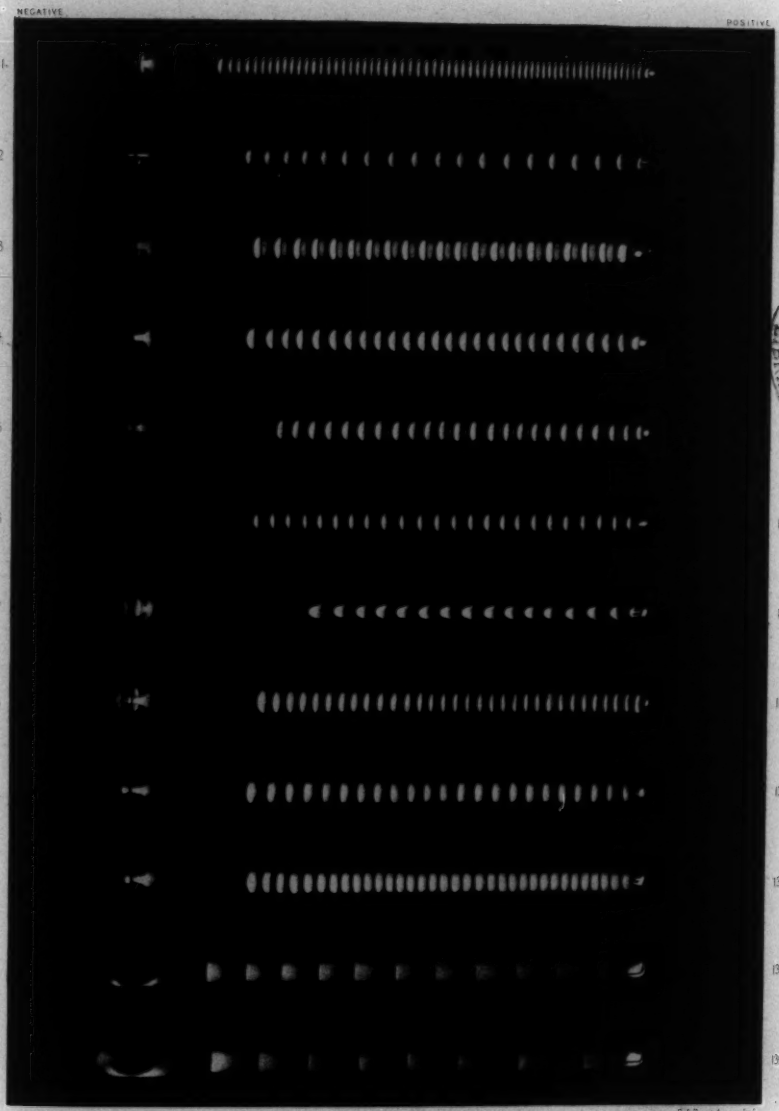
FAC-SIMILE OF PHOTOGRAPHS



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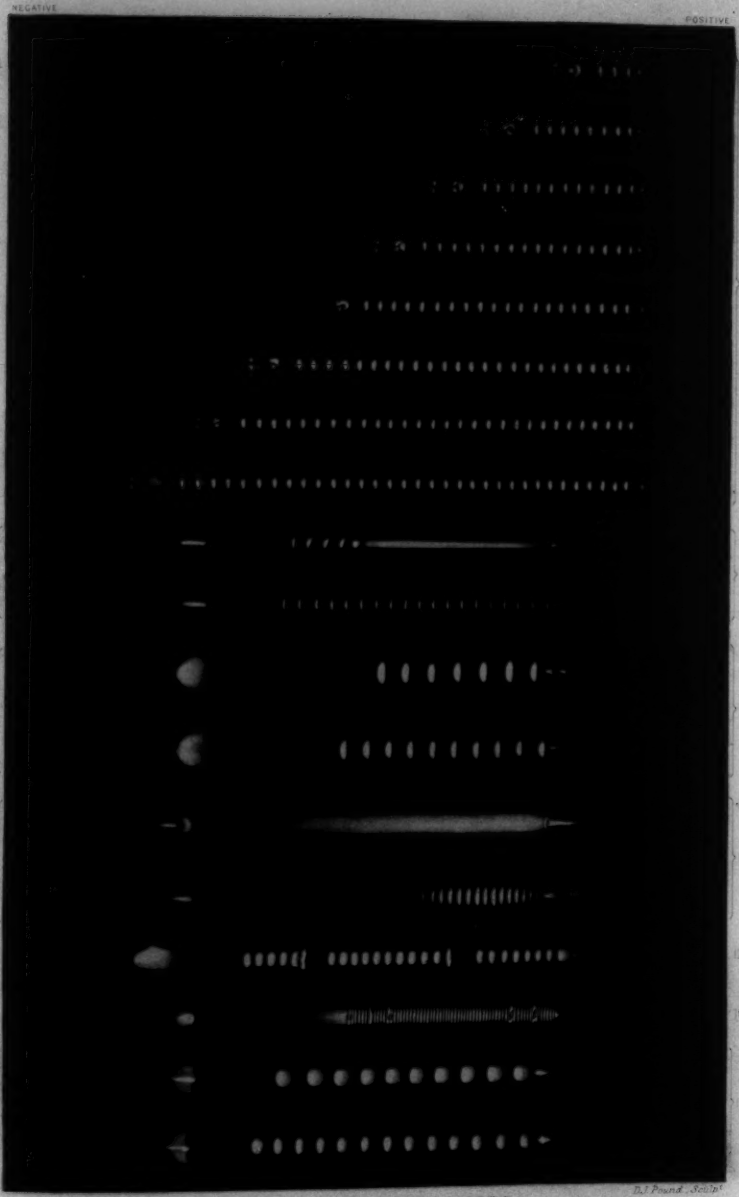
FAC-SIMILE OF PHOTOGRAPHS.

B.J. Pound, sculp.



FAC-SIMILE OF PHOTOGRAPHS.

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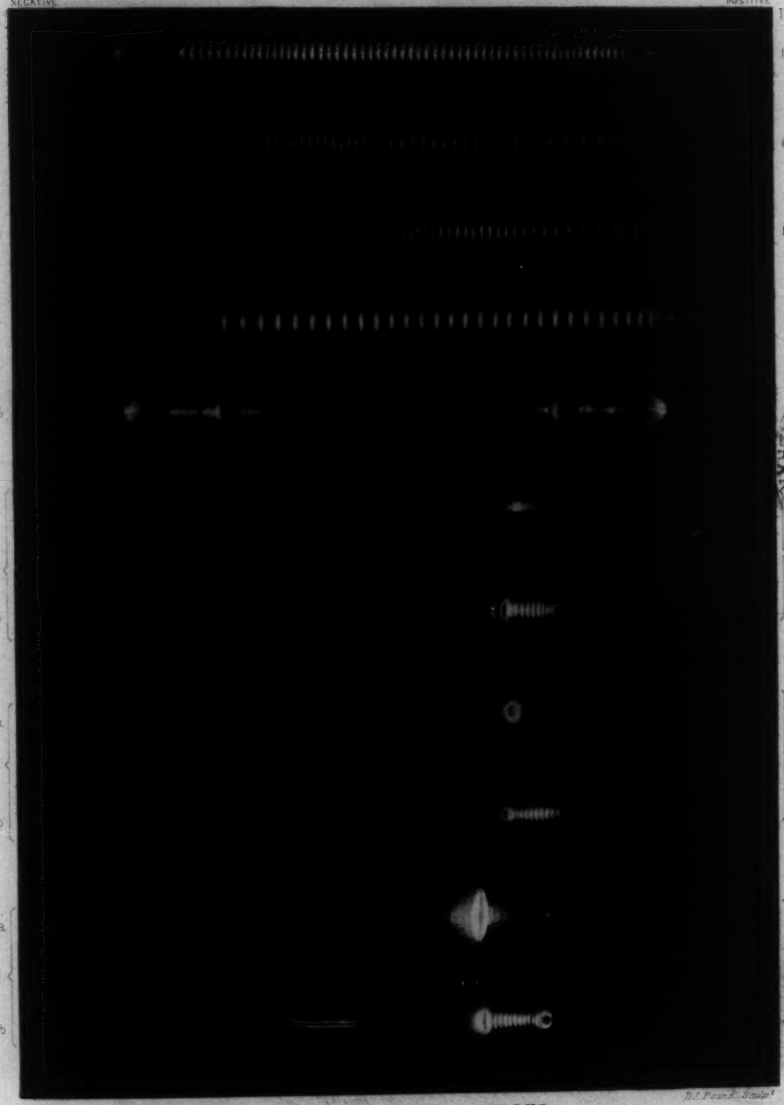

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